Lehigh University
Lehigh Preserve

Theses and Dissertations

1987

Quantitative shape analysis of benthic foraminifera from southern Maryland :

Stephen J. Cauller
Lehigh University

Follow this and additional works at: https://preserve.lehigh.edu/etd

Part of the Geology Commons

Recommended Citation
Cauller, Stephen J., "Quantitative shape analysis of benthic foraminifera from southern Maryland :" (1987). *Theses and Dissertations*. 4800.
https://preserve.lehigh.edu/etd/4800

This Thesis is brought to you for free and open access by Lehigh Preserve. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of Lehigh Preserve. For more information, please contact preserve@lehigh.edu.

QUANTITATIVE SHAPE ANALYSIS OF BENTHIC FORAMINIFERA FROM SOUTHERN MARYLAND - A NEW APPROACH TO THE PALEOECOLOGY OF THE MIDDLE MIOCENE

by

Stephen J. Cauller

A Thesis

Presented To The Graduate Committee

of Lehigh University

in Candidacy for the Degree of

Master of Science

in

Geology

Lehigh University

1987

CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science

Sept. 14, 1987
(Date)

James M. Porter
Professor in Charge

Sept. 14, 1987
(Date)

Bob Carlson
Chairman of Department

ACKNOWLEDGEMENTS

Special thanks are extended to Dr. James M. Parks who served as thesis advisor for this project. His guidance, direction, helpful discussions, programming assistance and generous use of computer programs are greatly appreciated. Special thanks are also extended to thesis committee members, Drs. J. Donald Ryan and Bobb Carson for their critical review of this document.

The logistical help of Dave Bohaska of the Calvert Marine Museum is gratefully acknowledged. His well established network of "scientifically conscious" private property owners along Calvert Cliffs was invaluable in the field. Gracious thanks are offered to property owners: Mr. Charles Shinn, Mrs. Sandy Roberts, Mr. Larry Smith, Mrs. Margaret Moran, Mr. & Mrs. Callis and Mr. Charles Stamm; for their permission to access cliff exposures on their property. The author would like to thank several fellow graduate students at Lehigh University for their help during this project, noteably Steven Siwiec for many insightful discussions, Robert Gibson and Robert Bond for their assistance in the field and Tracy Glassburn for her help in the field as well as her eagerness to discuss the geology of southern Maryland.

Financial support during this project came from Professor Parks' grain shape analysis research grants as well as graduate teaching assistantships provided by the Department of Geological Sciences at Lehigh University. A research grant from Standard Oil of California helped cover field expenses.

Finally, I would like to express my appreciation for the encouragement, love and support of my parents throughout my academic career and to my wife, Jean for her unending patience, confidence, support and love.

TABLE OF CONTENTS

Abstract	1
1. Introduction	3
2. Previous Work	5
3. Study Area	10
3.1 Regional Geology	10
3.2 Calvert Formation	12
3.3 Choptank Formation	15
3.4 Paleoecology	18
4. Methods	22
4.1 Sample Collection	22
4.2 Data Collection	26
4.3 Data Processing and Analysis	28
4.3.1 Multivariate Rotation Method	28
4.3.2 Principal Components Analysis	33
4.3.3 K-Means Cluster Analysis	36
4.3.4 Multiple Discriminant Analysis	38
4.3.5 Graphical Comparisons	39
4.3.6 Q-Mode Cluster Analysis	39
5. Results	41
5.1 Principal Components Analysis	41
5.2 K-Means Cluster Analysis	43
5.3 Multiple Discriminant Analysis	47
5.4 Four Major Morphological Groups	50
6. Discussion	59
6.1 Summary Of Results	59
6.2 Paleoecological Significance	60
7. Conclusions	65
References	67
Appendix A.	72
Appendix B.	87
Appendix C.	88
Vita	93

LIST OF FIGURES

Figure 3-1:	Generalized stratigraphic column of the Calvert Formation.	**14**
Figure 3-2:	Generalized stratigraphic column of the Choptank Formation.	**17**
Figure 4-1:	Site location map with Calvert/Choptank and Choptank/St. Marys Formation contacts.	**23**
Figure 4-2:	Sample location map.	**27**
Figure 4-3:	Equipment used for data collection and processing.	**29**
Figure 4-4:	Reference shape used for E-W and/or N-S flip.	**30**
Figure 4-5:	Foraminiferal outline as represented by 36 rotated radial lengths.	**32**
Figure 5-1:	Principal component loading patterns and average shape derived from the reference sample (CS510).	**42**
Figure 5-2:	Thirty-two morphological groups. Original order determined by cluster analysis.	**45**
Figure 5-3:	Thirty-two morphological groups. Rearranged to reflect shape continuums.	**46**
Figure 5-4:	Graph of the percentages of 32 morpho-groups present within two samples from "Zone" 9.	**48**
Figure 5-5:	Graph of the percentages of 32 morpho-groups present within two samples from "Zone" 10.	**49**
Figure 5-6:	Bean shaped morphological groups.	51
Figure 5-7:	Polygonal morphological groups.	52
Figure 5-8:	Bulbous morphological groups.	53
Figure 5-9:	Elongate morphological groups.	54
Figure 5-10:	Two-dimensional dendrogram illustrating results from Q-mode cluster analysis of the 4 major morpho-groups.	58

LIST OF TABLES

Table 3-1:	Stratigraphy of the Chesapeake Group	10
Table 3-2:	Paleobathymetry of the Calvert & Choptank Formations	21
Table 4-1:	Principal Components Analysis Variable Definitions	35

ABSTRACT

The multivariate rotation method of quantitative shape analysis as developed by Parks (1981; 1982) was applied to a representative population of middle Miocene benthic foraminifera from the Calvert and Choptank Formations of the middle Atlantic Coastal Plain. Two-dimensional outlines of foraminifera tests were converted to X,Y coordinates (graphical representation of each shape), universally oriented and reduced to 36 equiangular radial lengths. Principal components analysis of radial length data further reduced each shape to six variables or principal component scores, accounting for approximately 90% of the original shape information. Q-mode cluster analysis and multiple discriminant analyses of component scores classified each foraminifera shape into one of 32 morphological groups.

Based on the relative percent of all 32 morpho-groups present within samples taken at discrete stratigraphic intervals, correlation of similar stratigraphic levels both along strike and down dip was achieved. Four major morphological groups: Bean, Polygonal, Bulbous, and Elongate; delineated from shape continuums of 32 morpho-groups demonstrated both intra- and interformational shape trends. Both graphical comparisons and Q-mode cluster analysis of four major morpho-group percentages indicated a gradual shift from bean shapes to elongate and asymmetric (polygonal and bulbous morpho-groups combined) shapes over time. Systematic distibution of benthic foraminiferal morphologies is inferred by the gradualistic nature of the observed shape trends. These trends closely

mirror a large-scale environmental shift in the Salisbury embayment during the middle Miocene from shallow, cool temperate marine waters to very shallow, cool to moderately warm water.

Water depth, either directly or indirectly is a major factor controlling numerous environmental parameters such as temperature extremes, salinity, turbidity, oxygenation and pH and substrate nature. These environmental factors undoubtably influence foraminifera growth as well as impact the distribution of species and consequently their associated morphologies. The shapes and shape trends observed are believed to reflect the the major ecological conditions which control their distribution.

CHAPTER 1

INTRODUCTION

With the advent of computer imaging techniques that are able to quantify entire two-dimensional shapes, it is now possible for accurate and objective quantitative comparisons of "shape" itself rather than comparisons based on some "characteristic component" of shape. Various methods of quantitative shape analysis (Clark, 1981) were originally developed as an interpretive tool in sedimentological studies of quartz grains. Numerous studies of quantitative grain shape (Mazzullo et. al., 1984; Gibson, 1985; Siwiec, 1986) have been successful in delineating provenance, transport history and depositional environments of sedimentary deposits.

The importance of objective recognition of distinct biologic shapes has been a critical aspect of paleontology ever since the identification of independent species and the inception of the species concept. Applying quantitative methods of shape analysis to biologic forms reduces the subjectiveness in an area of paleontology where only broad generalizations were made previously.

Benthic foraminifera are well suited for quantitative shape analysis. They are one of the most widely used living and fossil groups for reconstruction of environments and paleoenvironments of the marine bottom. Because the "life" environment of benthic foraminifera is believed to be a possible cause of variations in the number of species and the distribution of assemblages, as well as test shape, a study that quantifies shape variability among an entire fauna of benthic foraminifera has direct environmental implications (Bandy, 1964; Pflum and Frerichs, 1976).

The ability to constrain the paleoecology of the sediments and associated fauna is an important factor when attempting to apply a cause and effect relationship to an observed shape trend. The middle Miocene Calvert and Choptank Formations of Maryland and Virginia meet or exceed these criteria. Their excellent exposure over a considerable area of southern Maryland containing an abundance of well-preserved vertebrate and invertebrate (both macro- and microfauna) remains has resulted in a detailed determination of paleoecology throughout their depositional history (Gibson, 1962; Gernant et. al., 1971). Applying quantitative shape analysis to benthic foraminifera from these deposits allows for a strong comparison of shape variability to environmental factors.

This study utilizes the Multivariate Rotation Method of quantitative shape analysis, developed by Parks (1981, 1982), to meet the following objectives:

1. to quantify the range of shape variation within the entire population of benthic foraminifera from the middle Miocene Calvert and Choptank Formations of Maryland and Virginia;

2. to compare shape signatures of faunas from similar statigraphic levels within a defined geographic extent;

3. to identify the presence of any specific shape trends among the entire benthic foraminifera fauna; and,

4. to describe the relationship between any shape trends and the independently determined paleoecology of these stratigraphic units.

CHAPTER 2

PREVIOUS WORK

Since the development of computer technology with the ability for rapid and objective processing of large data matrices, work on the biologic analysis of shape has focused on quantification of entire outlines. Early biometric studies made widespread use of data on the gross dimensions of structures and of measurements between well defined "landmarks" but were unable to determine lengths of vectors or curves (Scott, 1980). The emphasis on gross dimensions has been due in part to instrument limitations (e.g. calipers), operational convenience and the precedents set by previous studies.

Shortly after the development of quantitative shape analysis (Schwarcz and Shane, 1969; Ehrlich and Weinberg, 1970) researchers applied various methods of this procedure to microfossils, specifically in numerous biometric studies of planktonic foraminifera (Scott,1975, 1976, 1979, 1980; Healy-Williams and Williams, 1981), in analysis of ecophenotypic shape variation with latitude of a planktonic foraminifer (Lohmann, 1983) and most recently in ascertaining evolutionary relationships between planktonic foraminifera genera (Belyea and Thunell, 1984). Apparently based upon precedents, quantitative shape studies of foraminifera have only been applied to planktonic species.

The relationship between foraminifera test morphology, habitat and environment has not been well studied. Noteable exceptions include Bandy

(1964) who correlated general trends in foraminiferal structure, composition and form with changes in bathymetry (ranging from inner shelf to abyssal depths) and temperature. Brasier (1975) related morphological adaptations of miliolidae foraminifera to the substrate stability of three generalized habitats. Chamney (1976) used chamber shape and arrangement as a basis for classifying predominantly agglutinated benthic foraminifera to aid in a large-scale correlation of marine environments and bathymetries.

Recently, the shape variation among benthic foraminifera has shown great promise in determining biofacies. Severin (1983) demonstrated the capability of distinguishing biofacies entirely from the test morphology of benthic foraminifera. Although Severin did not strictly apply quantitative shape analysis, he did show that the environment influenced the presence of specific shapes of Recent benthic foraminifera. Using the variations in shape within the entire benthic foraminiferal fauna, as expressed by six visually classified morphological groups, Severin was able to delineate four biofacies; bay, 0–30 m, 30–60 m, and 60–110 m — the same biofacies as those recognized by previous workers on the basis of species occurences (Severin, 1983).

Culver et. al. (1985) used variation in benthic foraminiferal morphology as a tool for paleoenvironmental and paleobathymetric interpretations. While this study did not compare foraminiferal outlines as does quantitative shape analysis, it used quantitative descriptors of benthic foraminifera tests describing test shape, chamber arrangement, apertural characteristics, and surface sculpture (Culver et. al., 1985). Cluster analysis established "morphological biofacies," of which many were depth related. Parks' multivariate rotation method of quantitative shape analysis (1982) has also been used (Aycox, 1985) to show the morphological variation in benthic foraminifera — specifically the change in shape with depth of two Holocene genera.

Quantitative shape analysis was established in the early 1970's by Schwarcz and Shane (1969) and Ehrlich and Weinberg (1970) as a procedure for describing the two-dimensional shape of quartz grains. The method allows shape to be quantitatively described on the basis that a two-dimensional projection of a grain is representative of its three-dimensional shape (Schwarcz and Shane, 1969). This early method approximated a grain's two-dimensinal outline by an expansion of the perimeter radius as a function of angle about the grain's center of gravity by a Fourier series (Ehrlich and Weinberg, 1970).

Several authors have noted inherent problems of the Fourier method possibly producing ambiguous results. The main contentions are as follows:

1. While harmonic amplitudes are rotation invariant, their associated phase angles are rotation dependent (Clark, 1981). Due to the difficulty of statistically processing paired data sets only the harmonic amplitudes are retained in Fourier shape analysis. As a result, phase angles and their associated shape information are ignored.

2. Distinctly different shapes could produce identical harmonic amplitude spectra and similar shapes could produce different harmonic amplitude spectra if phase angles are disregarded (Parks, 1981).

3. **The original shape cannot be reconstucted without the associated** phase angle information.

4. No simple relationship exists between a shape and the collection of harmonic functions that Fourier shape analysis attempts to fit to it, especially for asymmetric forms such as most foraminifera (Bookstein et. al., 1982).

Although the Fourier procedure has several intrinsic problems it has been closely followed by numerous investigators in quartz grain and both macro- and microfossil shape studies.

Parks (1981) developed the Multivariate Rotation Method of quantitative shape analysis as an alternative to Fourier shape analysis with its associated problems. This method has been successfully applied to shape studies of quartz grains (Parks, 1982, 1983a, 1983b; Collins, 1983; Gibson, 1985), carbonate sands (Mengel,1985), pebbles (Siwiec, 1986), benthic foraminifera (Aycox, 1985) and bivalves (Glassburn, 1987).

The Multivariate Rotation Method of shape analysis as applied in this study, initially entails electronically digitizing two-dimensional projected foraminiferal peripheries. This converts the silhouette into 100+ X,Y coordinate pairs. A Fortran computer program then rotates the outlines (represented by X,Y coordinates) to a common orientation and subsequently corrects for mirror images by reversing the image around a N-S and/or E-W axis to a least squares best fit with an oriented reference shape. The 100+ X,Y coordinate pairs representing each outline are then reduced by cubic interpolation to 36 points at 10 degree intervals about the computed center of gravity. Radial lengths, the distances from the computed center of gravity to each of the 36 points, are then computed.

The 36 rotated radial lengths representing each shape are further reduced by principal components analysis (PCA). A reference sample from this study, consisting of 340 shapes, is subjected to PCA, producing a "reference" principal component loadings matrix. PCA transforms the original 36 variables (many of which are highly correlated) to an equal number of orthogonal (uncorrelated) principal components. Only the first six components, which account for approximately 90% of the variance in the reference data set, are used in further steps of the analysis. The "reference" principal component loadings matrix is used on all subsequent data sets to calculate principal component scores with respect to a single set of orthogonal reference axes. This step is essential for valid comparisons of principal component scores between samples. The principal component scores are then subjected to various multivariate statistical procedures to ultimately unravel their paleoecological meaning.

CHAPTER 3

STUDY AREA

3.1 REGIONAL GEOLOGY

The Salisbury embayment is a structural basin extending from southern New Jersey through Delaware and southern Maryland to eastern Virginia. It has been a nearly continuous depocenter of marine sediments from Cretaceous through Pliocene time although both basin depth and boundaries have varied over time due to tectonic and eustatic controls.

The Chesapeake Group was originally defined for Miocene strata exposed along the western shore of Chesapeake Bay in southern Maryland. These deposits are exposed in a portion of the uplifted, landward extension of the Salisbury embayment. The Miocene Chesapeake Group of southern Maryland and eastern Virginia was divided into the Calvert (lower and lower middle Miocene), Choptank (middle middle Miocene), and St. Marys (upper middle Miocene) Formations by Shattuck (1902). The Chesapeake Group has subsequently been subdivided and expanded by several workers to include strata ranging in age from upper Oliogocene to upper Pliocene (Ward, 1984a, 1984b). These units are listed in Table 3-1.

TABLE 3-1

STRATIGRAPHY OF THE CHESAPEAKE GROUP

FORMATION	MEMBER/BEDS	AGE
Chowan River	Colerain Beach Member	upper Pliocene
	Edenhouse Member	upper Pliocene
Yorktown	Moore House Member	upper Pliocene
	Morgarts Beach Member	upper Pliocene
	Rushmere Member	upper Pliocene

	Sunken Meadow Member	lower/upper Pliocene
Eastover	Cobham Bay Member	upper Miocene
	Claremont Manor Member	upper Miocene
St. Marys	Windmill Point beds	upper middle Miocene
	Little Cove Point beds	upper middle Miocene
	Conoy Member	upper middle Miocene
Choptank	Boston Cliffs Member	middle middle Miocene
	St. Leonard Member	middle middle Miocene
	Drumcliff Member	middle middle Miocene
Calvert	Calvert Beach Member	lower middle Miocene
	Plum Point Marl Member	lower middle Miocene
	Fairhaven Member	lower and lower middle Miocene
Old Church		upper Oligocene and lower Miocene

From Ward (1984a, 1984b)

The Calvert, Choptank and St. Marys Formations of Maryland were subdivided into 24 "Zones" by Shattuck (1904) based on lithologic character and/or the presence or absence of laterally traceable macrofossil beds. In Shattuck's scheme, "Zones" 1-15 comprise the lowermost formation, the Calvert; the overlying Choptank was divided into "Zones" 16-20; and the St. Marys Formation, the uppermost unit, consists of "Zones" 21-24. While other coastal plain workers have proposed different classification schemes for these formations (see Dryden, 1936; Kidwell, 1984), Shattuck's subdivisions have persisted in the literature. Gernant (1970) elevated Shattuck's "Zones" 16-20 of the Choptank Formation to member status: Calvert Beach Member (Zone 16), Drumcliff

Member (Zone 17), St. Leonard Member (Zone 18), Boston Cliffs Member (Zone 19) and the Conoy Member (Zone 20).

3.2 CALVERT FORMATION

The Calvert Formation was divided into two members by Shattuck (1904): the Fairhaven Diatomaceous Earth ("Zones" 1-3) and the Plum Point Marls ("Zones" 4-15). Ward (1985) separated Shattuck's "Zone" 1 into the Old Church Formation leaving the Fairhaven Member consisting of "Zones" 2 and 3. The Fairhaven rests unconformably on the Old Church Formation (Ward, 1984a, 1984b). This member is about 60 feet thick at its type locality and consists of a basal transgressive, argillaceous sand overlain by a silty diatomaceous earth composed of up to 60% diatom tests (Glaser, 1968). This lithology grades up into a homogeneous, fine argillaceous sand. Macrofauna are found sporadically throughout the Fairhaven and consist predominantly of pelecypods (molds and casts), shark teeth, fish vertebrate and other bone fragments. The Fairhaven sediments have been deeply leached, removing virtually all carbonate (Glaser, 1968). Microfossils, except for diatoms, are absent from all but the upper few feet of sediment (Gibson, 1962), hence this member was not studied in this investigation.

The Plum Point Member unconformably overlies the Fairhaven Member. The strata consist of bluish-gray to grayish-brown and buff sandy clays with several highly fossiliferous horizons. In contrast to the Fairhaven Member, the Plum Point Member is extremely fossiliferous. Macrofauna include numerous vertebrates and a proliferation of mollusks — 231 species have been described by Clark et. al. (1904). Microfauna are also numerous, including diatoms, ostracoda and foraminifera. Gibson (1962) identified 41 species of benthic foraminifera from the Calvert Formation, the majority of which are from the Plum Point Member. The Plum Point Member has been subdivided into a number of "Zones" (4-15) based on fossil content and/or lithology. "Zone" 10 near the base of the member is a thick, laterally traceable shell bed which is widespread and diagnostic of the Calvert Formation. This shell bed is exposed along Calvert Cliffs from near Chesapeake Beach to 2-3 miles south of Plum Point where it dips below the beach, and at numerous inland exposures. In addition, "Zones" 12, a bone bed, and 14 are highly fossiliferous. Figure 3-1 is a generalized stratigraphic column of the Calvert Formation illustrating these "Zones".

The upper contact of the Calvert Formation with the overlying Choptank Formation has been a topic of debate ever since Shattuck established it at an unconformity he felt existed between his informal lithologic "Zones" 15 and 16. The placement of this contact was based on his recognition of an unconformity between "Zones" 15 and 17 at Parker Creek in the Calvert Cliffs and Shattuck's extrapolation that that the unconformity must exist elsewhere between "Zones" 15 and 16. The majority of subsequent workers have had trouble not only confirming this unconformity but locating the contact as it appears to be gradational.

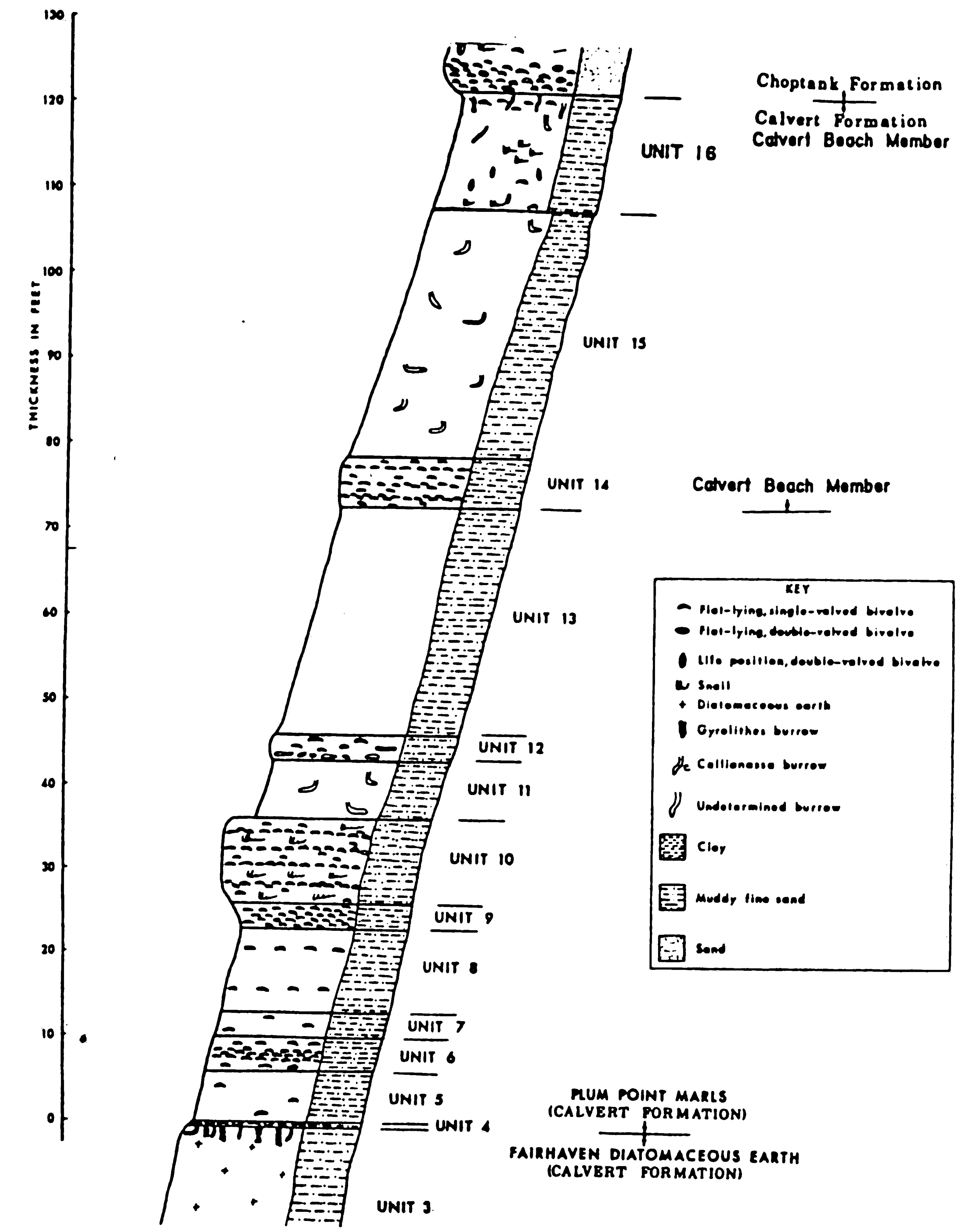


Figure 3-1: Generalized stratigraphic column of the Calvert Formation. Unit designations correspond to Shattuck's "Zones". Modified from Gernant (1971).

Kidwell (1982) recommended that the contact between the Calvert and Choptank be placed between the Calvert Beach Member ("Zone" 16) and the Drumcliff Member ("Zone" 17). Kidwell based this proposal on observations that "Zones" 15 and part of 16 "are not vertically successive units separated by an unconformity but are instead two, slightly overlapping facies of a single laterally continuous unit." As further evidence Kidwell mentioned that "Zones" 15 and 16 (her Turritella-Pandora interval) are an interbedded muddy sand and clay containing thin stringers of shell with an upper contact that is a disconformity. Ward (1984a, 1984b) followed Kidwell (1982) and placed the Calvert/Choptank contact between the Calvert Beach Member and the Drumcliff Member. In addition he expanded the Calvert Beach Member (originally only "Zone" 16) to include Shattuck's "Zones" 14-16. In this context the Calvert Formation now consists of three members — the Fairhaven Member ("Zones" 2 & 3), Plum Point Member ("Zones" 4-13) and Calvert Beach Member ("Zones" 14-16).

3.3 CHOPTANK FORMATION

The placement of both the Choptank's lower and upper contacts with the Calvert and St. Marys Formations respectively, have been the subject of recent revision. The lower contact as discussed previously, is placed at the disconformable base of the Drumcliff Member ("Zone" 17). Recent field examinations in Maryland and Virginia (Blackwelder and Ward, 1976; Newell and Rader, 1982) have shown that the upper beds of the Choptank, the Conoy Member ("Zone" 20), are laterally equivalent facies with the lower beds of the St. Marys. Therefore, the Conoy Member, although inappropriately established in a field guide, is now considered the basal member of the St. Marys Formation (Ward, 1984a, 1984b). In essence, the five members of the Choptank as defined by Gernant (1970), have been reduced to three with the lowest member, the Calvert Beach Member, placed in the Calvert Formation and the uppermost member, the Conoy Member, marking the base of the St. Marys Formation. The abbreviated Choptank Formation now consists of the Drumcliff Member ("Zone" 17), the St. Leonard Member ("Zone" 18), and the Boston Cliffs Member ("Zone" 19). Figure 3-2 is a generalized stratigraphic column of the Choptankk Formation illustrating these recent revisions.

The Choptank Formation is a clastic unit consisting of fine yellowish-brown quartz sand and dense bluish-green, sandy clay. Occasional indurated layers are noteworthy, especially along Drumcliff, the typesection of the Drumcliff Member. Abundant fossil remains are disseminated throughout the formation. The Drumcliff Member ("Zone" 17) and the Boston Cliffs Member ("Zone" 19) are well-defined shell beds composed of tightly-packed molluscan shells in a matrix of well sorted, fine yellowish-brown sand. The Drumcliff Member ranges from 6 to 30 feet while the Boston Cliffs Member varies less, ranging from 12 to 15 feet (Glaser, 1968). The intervening St. Leonard Member is relatively unfossiliferous, attains a maximum thickness of 18 to 22 feet and consists of bluish-green muddy fine sands to silts along Calvert Cliffs.

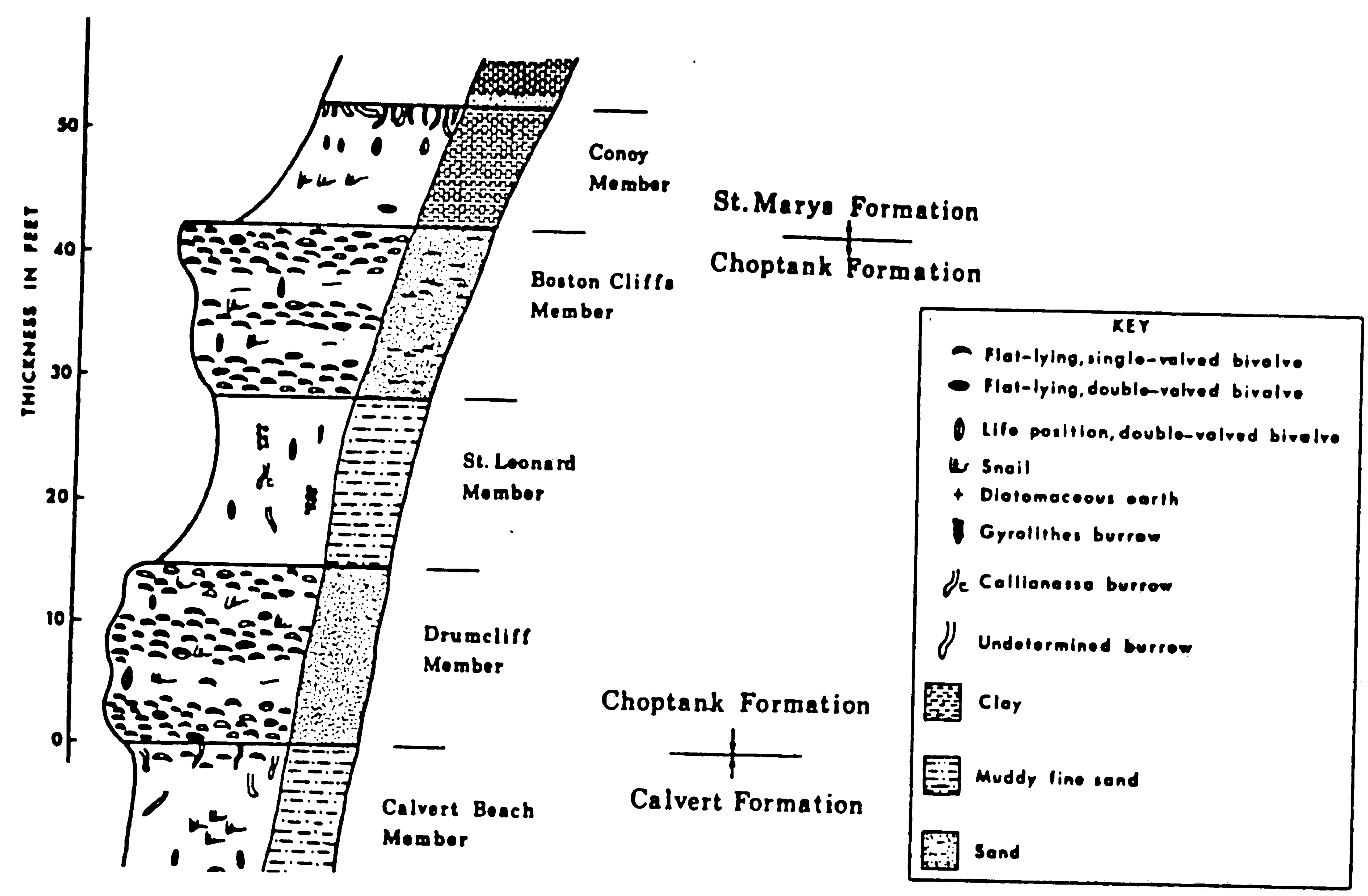


Figure 3-2: Generalized stratigraphic column of the Choptank Formation. Modified from Gernant (1971).

Choptank macrofauna consist of approximately 190 species of mollusks, several fish, echinoderms, bryozoans, sparse brachiopods, and one coral (Clark et. al., 1904). Microfossils are also abundant, consisting predominately of ostracoda and foraminifera with sparser diatoms. Gibson (1962) reports 41 species of benthic foraminifera from the Calvert Formation.

3.4 PALEOECOLOGY

The first comprehensive study of the Miocene Chesapeake Group's paleoecology was that of Gibson (1962). Work by Gernant (1970) on the Choptank Formation and further analysis and summaries by Gernant (1971), McLean (1969, 1970) and Kidwell (1982) aided in detailed determination of paleoenvironment and paleobathymetry of the Calvert and Choptank Formations. These results are summarized in Table 3-2. The following discussion, unless otherwise noted, follows Gibson (1962).

Comparisons of benthic foraminifera faunas with the present distribution of the same species indicates deposition of the Calvert and Choptank in marine waters generally much shallower than 100 meters. The Calvert Formation was generally deposited in cool, shallow, temperate marine water with both a shallowing and slight warming trend present in the upper units. In general, the Choptank Formation was deposited in very shallow, cool to moderately warm waters. Apparently the Choptank was deposited in shallower water than much of the Calvert. This is indicated by the presence of certain benthic foraminifera such as

Miliammina fusca, which are indicative of very shallow marine to brackish waters. The shallowing trend of the upper Calvert continues into the lower part of the Choptank.

McLean (1970) points out that the Choptank's microfauna is indicative of a relatively restricted environment in contrast with the underlying Calvert Formation, most likely in response to the decrease in basin size during Choptank time. Malkin's (1953) study of the ostracoda of these formations suggested that the Choptank sediments may represent less saline waters than those of the Calvert because of a greater proportion of ostracoda to foraminifera in the Choptank samples. McLean's statistical analysis of Gernant's (1970) faunal data from the Choptank and Gibson's (1962) faunal data on the Calvert, Choptank and St. Marys Formations indicates much shallower paleodepths than those reported by Gernant (1971). "The relatively sparse record for the Calvert indicates a preference of fauna in that formation for depths ranging from 0-20m; the Choptank seems to have shifted to a more median depth of 10 to 30m" (McLean, 1970; see Table 3-2 for details). Kidwell's (1982) detailed examination of depositional cycles within the Calvert and Choptank Formations supports the earlier interpretations of Gibson and Gernant. "Following an initial transgression to deep sublittoral marine environments, the Plum Point Member of the Calvert Formation and the Choptank Formation record an overall regressive phase of deposition in the Chesapeake basin. This large-scale pattern is revealed by the increasing physical and paleoecologic heterogeneity of successive depositional sequences, slight but insistent coarsening up, increasing small-scale lithologic variability and the appearance of assemblages tolerant of reduced water salinities" (Kidwell, 1982).

TABLE 3-2

PALEOBATHYMETRY OF THE CALVERT & CHOPTANK FORMATIONS

Formation	"Zone"/ Member	Gernant 1970/1971	McLean 1970	Kidwell 1982
Choptank	19/Boston Cliffs	25 to 35 meters of cool, temperate ocean water.	10 to 20 meters generally	Subaerial? to very shallow sublittoral
	18/St. Leonard	Up dip facies- lower bay environment. Normal marine salinity or higher.	10 to 30 meters	Very shallow sublittoral to shallow sublittoral
	17/Drum Cliff	Deposited in 8 to 25m of open ocean water. At Nomini Cliffs, deposited in about 35 to 50m of ocean water.	Mostly at 20m, go to 10m, one sample goes to 40m.	Subaerial? to very shallow sublittoral
Calvert	16/ Calvert Beach	Lower part- 45 to 65m of open ocean water. Central and upper part- shallow inner shelf conditions.	10 to 30 meters	Very shallow sublittoral
	15/ Calvert Beach	Sparsely fossiliferous- No depth data.		Intermediate to very shallow sublittoral
	14/ Calvert Beach	Regression to approx. 35 to 50m of open ocean water.		Littoral? to shallow sublittoral
	13/Plum Point	Sparsely fossiliferous- No depth data.		Intermediate sublittoral to very shallow sublittoral
	12/Plum Point	Deposited in waters perhaps as deep as 75 to 80m.		Deep sublittoral
	11/Plum Point	Transition back to deeper waters.		Deep sublittoral
	10/Plum Point	Approx. 30 to 40m of open ocean water		Littoral? to shallow sublittotal
	5 - 9/ Plum Point	Depth increase to possibly 40 to 55m of open ocean water. Greatest depth during deposition of Zone 8 Zone 9 marks beginning of shallowing phase.		Intermediate sublittoral to shallow sublittoral
	4/Plum Point	Pyncnodote percrassa bed. Depth of abou 25 to 35m.		Shallow sublittoral

CHAPTER 4

METHODS

4.1 SAMPLE COLLECTION

A nearly continuous, complete section of the Maryland Miocene is exposed along the western shore of Chesapeake Bay from Chesapeake Beach south to Little Cove Point, Maryland. The Middle Miocene strata, Calvert, Choptank and St. Marys Formations, collectively are about 300 feet (92m) thick where exposed along the Calvert Cliffs although the cliffs attain a maximum height of 100 feet (31m) at a given location. Because of the regional dip of these units of approximately 10 feet/mile to the southeast, virtually the entire Miocene section is progressively transected heading south from Chesapeake Beach where the Fairhaven-Plum Point contact is exposed to Little Cove Pt. where the St. Marys Formation outcrops — a distance of approximately 25 miles (40km; Figure 4-1).

Samples were collected from numerous exposures within southern Maryland and northeastern Virginia. The majority of samples were collected along a transect of the Calvert Cliffs (Calvert County) on the western shore of Chesapeake Bay from Randle Cliff at the northern extent to just south of Calvert Beach at the southern extent. The Drumcliff Member was sampled at its type locality, at Drum Cliff along the western shore of the Patuxent River. One inland exposure of the Calvert Formation ("Zone" 10) was sampled in a ravine off Md. 381 (Prince George's County), just south of the town of Aquasco. Nomini Cliffs along

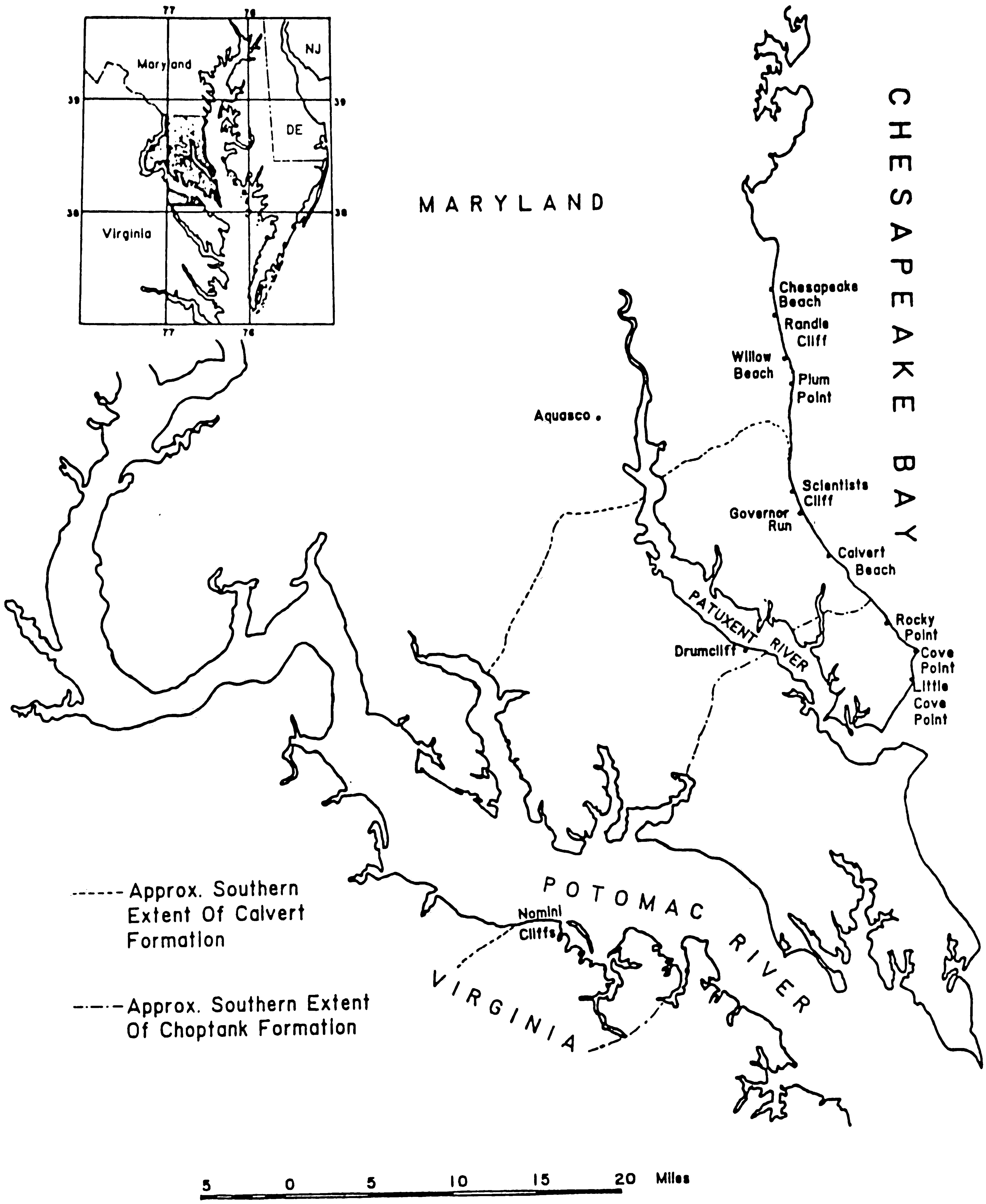


Figure 4-1: Site location map with Calvert/Choptank and Choptank/St. Marys Formation contacts.

the western shore of the Potomac River (Westmoreland County) in northeastern Virginia exposes the upper Calvert and Choptank Formations. This locality, near the southern terminus of the Choptank Formation, was the only location sampled in Virginia.

A total of 75 samples were collected at discrete stratigraphic intervals (spot samples) from the Calvert (Fairhaven Member excluded), Choptank and St. Marys Formations. All the samples were obtained from cliff exposures. The field method entailed using a trowel to clear the interval being sampled of several inches of outer sediment, effectively exposing fresh, uncontaminated sediments. Large blocks of fresh sediment were then cut out of the cliff and all surfaces of the blocks were broken off to further reduce the possibilty of sample contamination. The remaining sediment was bagged, and sediment and macrofossil descriptions, stratigraphic interval ("Zone", etc.) and locality were recorded.

The samples were then returned to Lehigh University for processing in a sedimentological laboratory. This step of the analysis required splitting the sample to obtain a 250g. (dry weight) subsample for processing. The sample was soaked and shaken in a sodium metaphosphate solution to disperse sediment particle aggregates. The sediment was then wet sieved over a 4.0 phi (63 μm) sieve to release the silts and clays. Because foraminifera are larger than 63 microns, they are retained with the coarse sediment fraction. The sand fraction (>4.0 phi) was dried and subsequently sieved through a stack of 1.0 phi (500 μm), 2.0 phi (250 μm), and 2.75 phi (150 μm) sieves with a residue pan (63-149 μm) at the bottom. Generally, most foraminifera are found in the 2.0 phi (250 μm) and 2.75 phi (150 μm) size fractions. All size fractions were checked for foraminifera. The 2.0 phi fraction (250 μm) was found to consistently contain the largest number of both individuals and species, and adult forms. The 2.75 phi (100 μm) size fraction was the only other fraction found to contain foraminifera — generally juveniles. Therefore, only these two size fractions were picked for foraminifera with the main emphasis concentrated on the 2.0 phi fraction. This series of steps significantly reduced the volume of sediment for foraminiferal picking.

The benthic foraminifera were picked from the loose sediment with a moistened artist's brush under a binocular optical microscope. They were then mounted on a clear glass microscope slide with gum tragacanth solution - a relatively transparent, water soluable, non-shrinking adhesive. One hundred or more forams were mounted per slide with the dorsal side down, establishing a stable, morphologically-standard position. This orientation also ensures that the plane of maximum two-dimensional projection, containing the maximum shape information, is projected.

Two criteria were essential for utilizing a sample in the succeeding analysis: benthic foraminiferal abundance and preservation. A minimum standard of 300+ well preserved, complete individuals per sample was established so that a statistically valid data base would be produced. While the majority of samples contained foraminifera, a significantly smaller number met these criteria. Generally, the samples that contained an abundant fauna were well preserved and those that only had a sparse fauna contained individuals that were often partially broken or otherwise poorly preserved. The St. Marys Formation was sampled and initially included in this study but only one sample collected from this formation met the above criteria. As a result the St. Marys Formation was excluded from the study reducing the number of samples to 55. Strict adherence to the aforementioned criteria further reduced the data base to 15 samples representing 4500+ foraminifera. Figure 4-2 contains the location of the samples used in this study.

4.2 DATA COLLECTION

The glass slides with the mounted foraminifera were placed on the stage of a microprojector and each silhouette was projected onto a Houston Instruments digitizing tablet. To electronically digitize the shapes, a cursor was manually traced around the periphery of each outline completing a closed form with the tablet in the switch stream mode. The position of the cursor cross-hairs was sampled at 25 millisecond intervals, converting the two-dimensional outline into a series of paired X,Y coordinates. Approximately 150-200 coordinate pairs were collected for each foraminiferal image. This procedure was followed for 300+ foraminifera in each sample and the resulting X,Y coordinate data was stored on floppy disks for later analysis.

The hardware utilized for this step is illustrated in Figure 4-3.

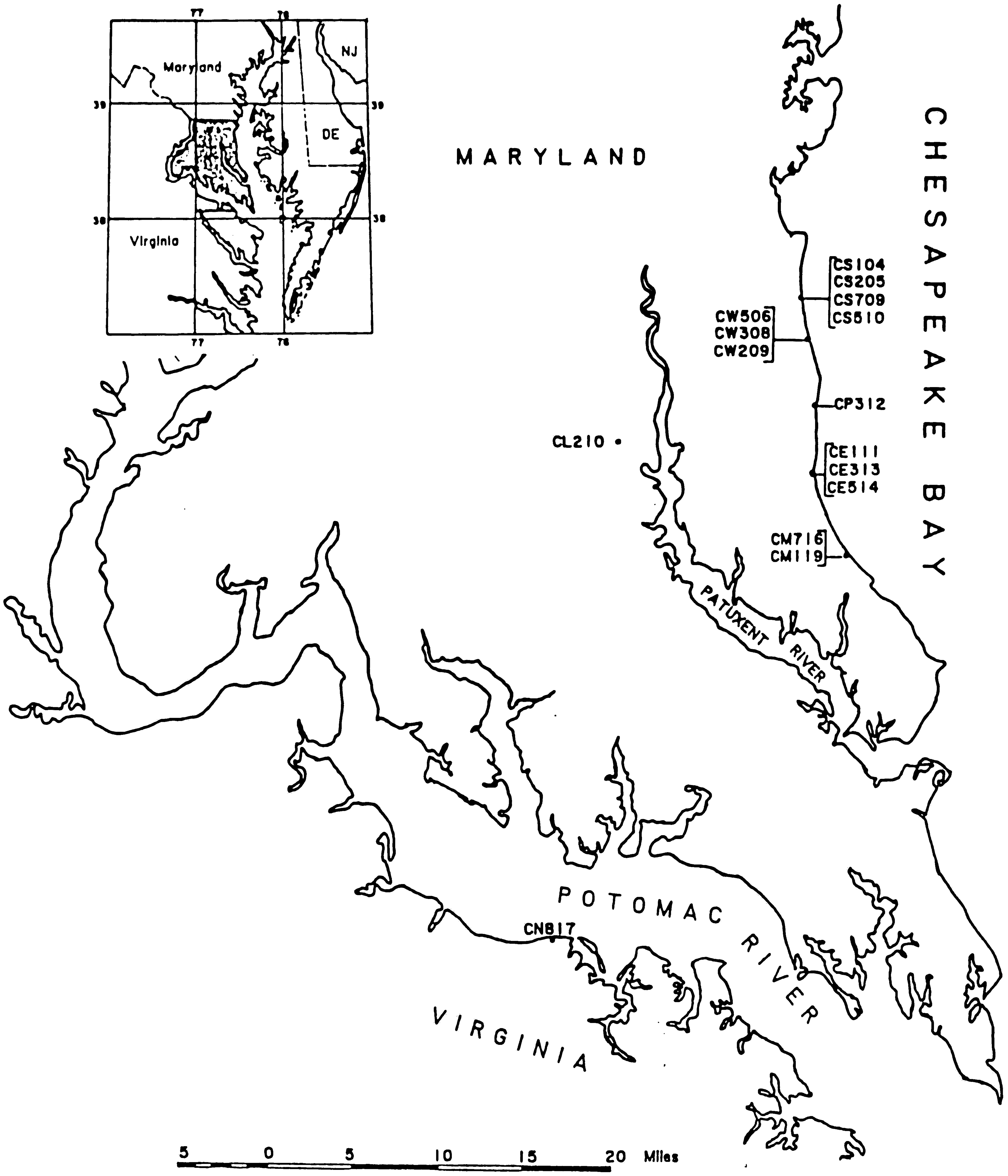


Figure 4-2: Sample location map. Last two numbers of the sample I.D. indicate "Zone".

It consists of a Fisher microprojector, a Houston Instrument Hipad II electronic digitizing tablet which is interfaced with a Zenith 148 microcomputer, an external 10 megabyte Winchester hard disk drive for program and data storage and a network interface (similar to a modem) with a mainframe computer.

4.3 DATA PROCESSING AND ANALYSIS

4.3.1 MULTIVARIATE ROTATION METHOD

The X,Y coordinate pair data representing each foraminiferal outline was processed with a set of Fortran computer programs, designed for an IBM-PC compatible microcomputer. The initial data processing consists of two main steps — rotating and flipping the shapes to a common orientation; and subsequent reduction of the digitized data to 36 points (radial lengths).

The rotation program rotates the foraminiferal outlines, represented by the X,Y coordinates, to a common orientation using a principal axes algorithm (from Tough and Miles, 1984) and subsequently corrects for mirror images by reversing the image around a N-S and/or E-W axis to a least-squares best fit to an oriented, asymmetric reference shape. The reference shape utilized in this study is illustrated in Figure 4-4. An algorithm by Hall (1976) was used to calculate the center of gravity of each outline. The outlines, represented by 100+ X,Y coordinate pairs are reduced by a cubic interpolation procedure to 36 radial lengths at 10

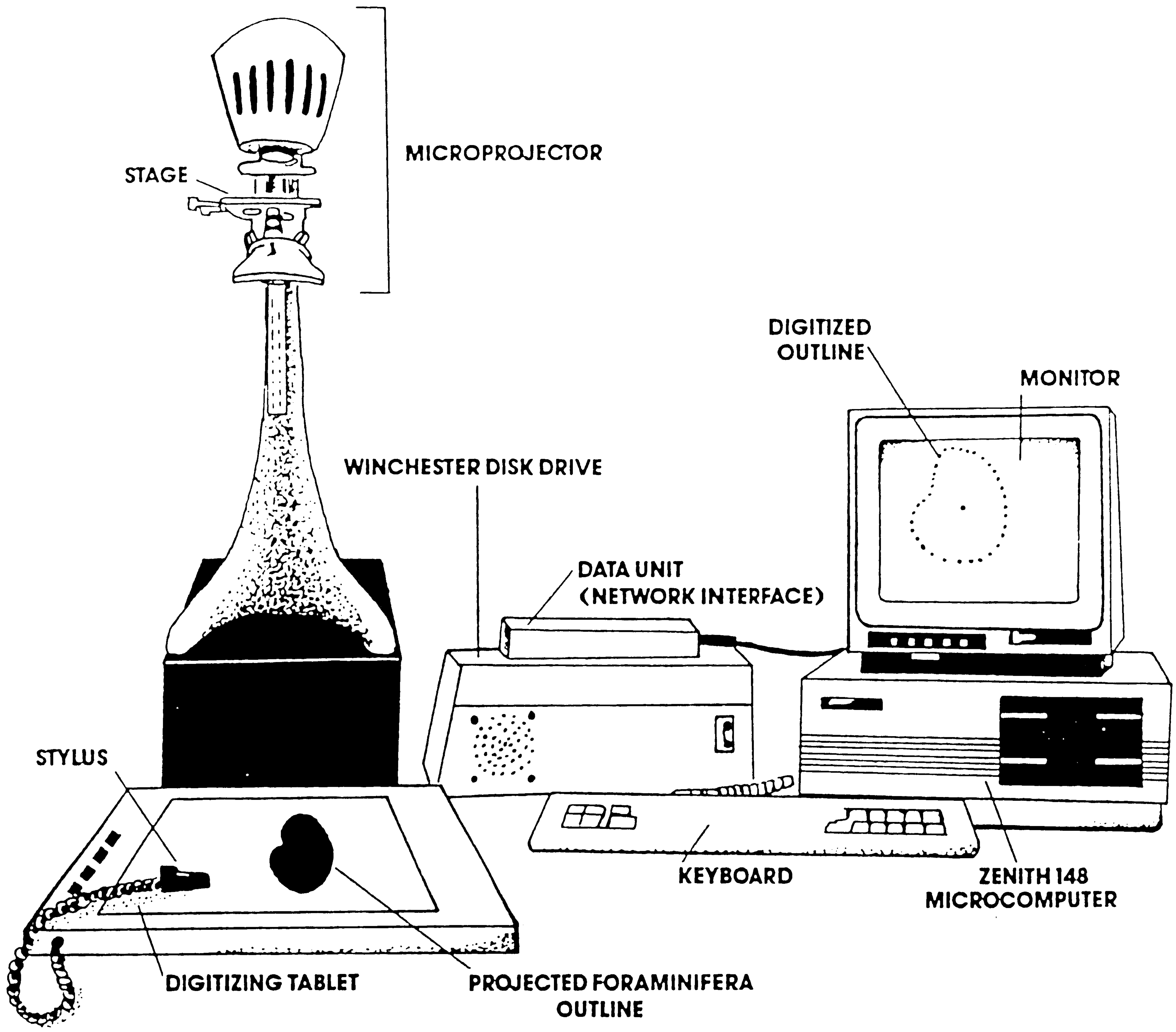


Figure 4-3: Equipment used for data collection and processing.
(Illustration by Jean Cauller)

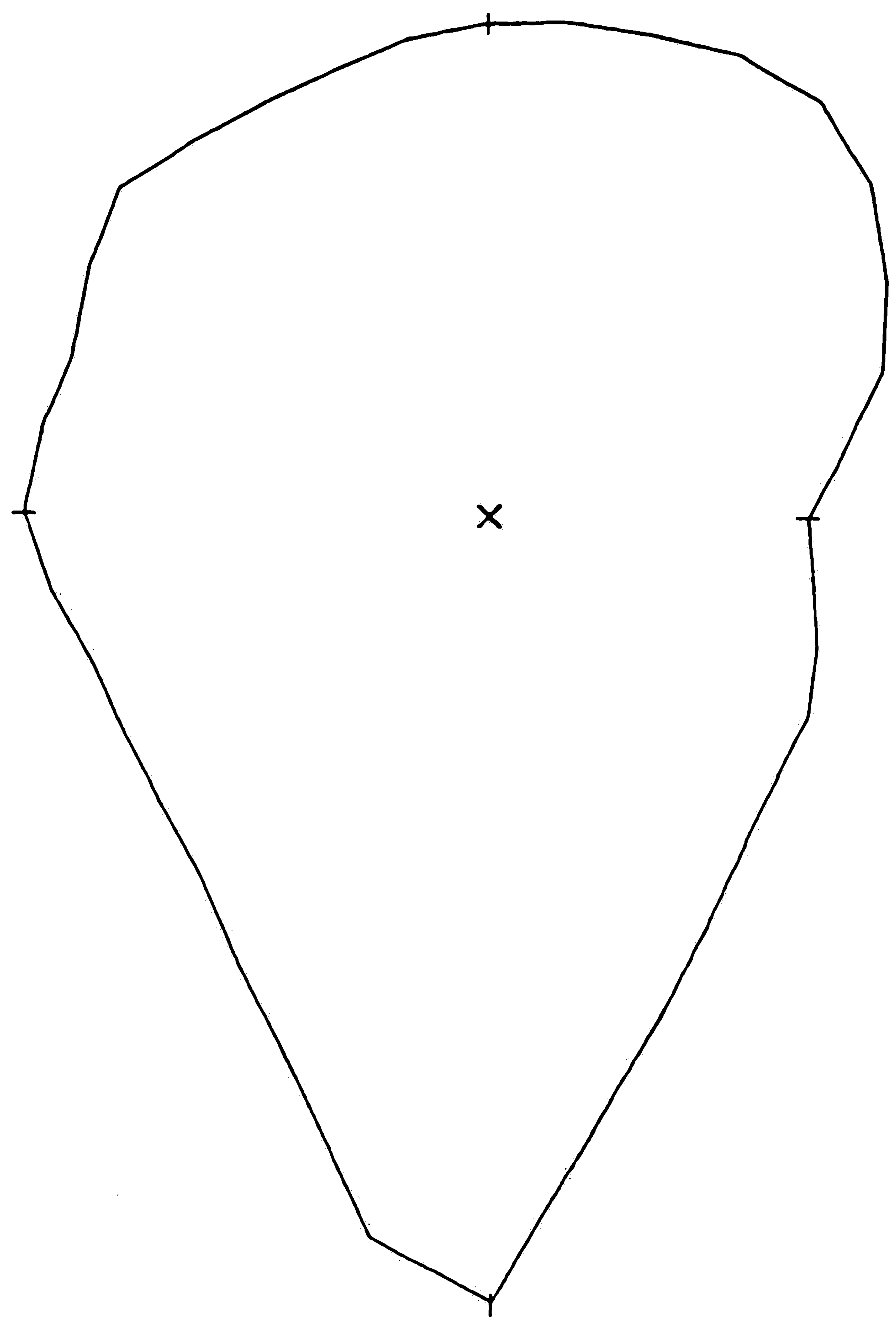


Figure 4-4: Reference shape used for E-W and/or N-S flip.

degree increments about the computed center of gravity. The radial lengths are normalized to a unit area for each foraminiferal outline eliminating any possible size affect. A foraminiferal outline represented by 36 rotated radial lengths is illustrated in Figure 4-5.

The principal axes algorithm (Tough and Miles, 1984) used in this study was extremely successful in aligning the foraminiferal outlines along a universal elongation axis. The effectiveness of this algorithm, producing mutual alignment of shapes, may indicate an inherent growth pattern in these benthic foraminifera which preserves a common, major axis of growth translation.

A second Fortran program was used to edit the rotated radial length files. It was implemented after visual comparisons of the computer-plotted rotated and flipped foraminiferal outlines with the original specimens indicated that an incorrect flip (mirror image) had occured. This program allowed the operator to open the rotated lengths file, read and plot the shape on the screen and to either flip the image N-S and/or E-W (reorder the rotated radial lengths), skip an outline or read the next one. In this manner, common orientation of all the foraminiferal shapes was achieved without a significant reduction of outlines due to incorrect flips, allowing for meaningful comparisons between samples. These procedures achieve two primary goals — universal orientation of all shapes for meaningful comparisons and a significant reduction in the amount of data (150-200 X,Y coordinates to 36 RRL/outline) without an appreciable loss of information.

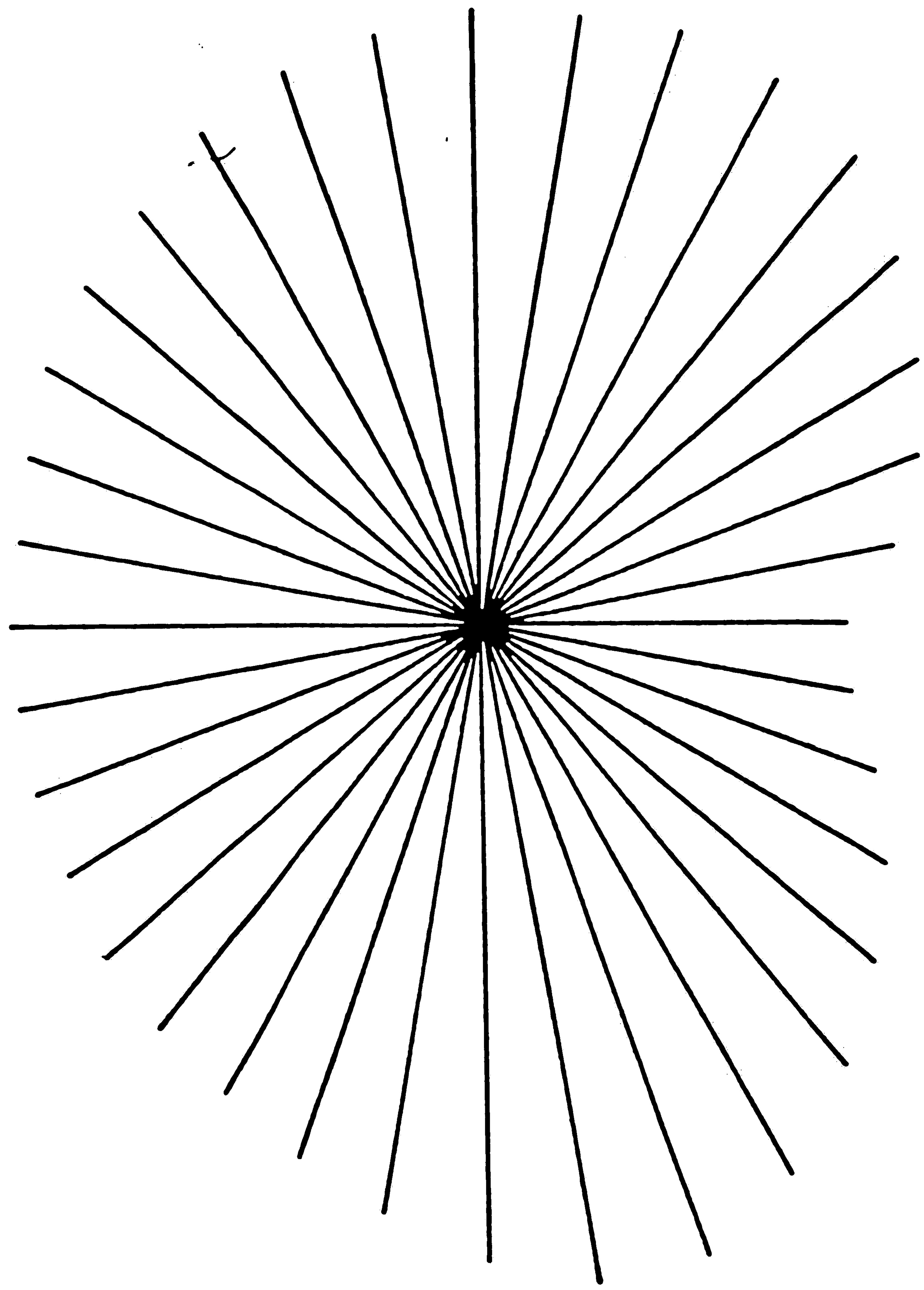


Figure 4-5: Foraminiferal outline as represented by 36 rotated radial lengths.

4.3.2. PRINCIPAL COMPONENTS ANALYSIS

Principal components analysis (PCA) consists of a linear transformation of 'p' original variables to 'p' new variables, with each new variable being a linear combination of the observed variable (Davis, 1986). The linear functions when represented geometrically as vectors are mutually orthogonal. The first principal component always accounts for the maximum variance of all the linear functions derivable from the given variables, the second principal component accounts for the greatest proportion of the residual variance of all the linear functions of the given variables that are orthogonal to the first principal component and so on. When there are a large number of variables such as 36 rotated radial lengths, a large majority of the variance in the raw data matrix is accounted for by a relatively small number of components. The coefficients of the principal components are the principal component loadings and the measurements of the principal components upon each of the individuals are the principal component scores. In this analysis 6 principal component scores accounted for 88% of the variance in a reference sample consisting of 36 variables (36 RRL) and 340 observations (forams). Principal components are simply the eigenvectors of the correlation matrix and may provide significant insight into the structure of the matrix (Davis, 1986).

A PCA produces components that are calculated with respect to orthogonal axes (reference frame) based on relationships within each specific data set. These orthogonal axes are oriented to maximize the variance within the given data and are specific to that particular sample. This makes comparisons of principal component scores from different samples measured from different orthogonal (reference) axes somewhat meaningless. To eliminate this problem a PCA, using an algorithm from Davis (1973), was applied to a specifically selected sample consisting of a broad spectrum of foraminiferal shapes. The principal component loadings from this analysis were extracted and stored. This "reference" principal component loadings matrix was then multiplied by the standardized data matrix of each sample to compute principal component scores that could be directly compared.

The principal component loadings matrix L computed from R, the matrix of correlations among the variables, is

$$L = A\,D^{\frac{1}{2}} \qquad (4.1)$$

where A is the matrix of unit-length eigenvectors of R and D is the diagonal matrix of eigenvalues. If the columns of F, the matrix of principal component scores, are standardized to have unit variance then

$$F^{*} = Z\,L\,D^{-1} \qquad (4.2)$$

where Z is the matrix of standardized data. By substituting (4.1) into (4.2) we get

$$F^{*} = Z\,A\,D^{-\frac{1}{2}} \qquad (4.3)$$

which is equivalent to dividing ZA by the standard deviations of the principal components. If the principal components are not standardized as employed in this study then

$$F = Z\,L \qquad (4.4)$$

where L is the principal components loadings matrix (Mather, 1976). Because of this relationship (4.4), principal component scores could be calculated for new data sets by postmultiplying their matrix of standardized data by the matrix of principal component loadings calculated from a "reference" sample.

TABLE 4-1

PRINCIPAL COMPONENTS ANALYSIS VARIABLE DEFINITIONS

n	- number of case
p	- number of variables
F	- (n x p) matrix of principal component scores
F^*	- (n x p) matrix of standardized principal component scores
Z	- (n x p) matrix of standardized data
L	- (p x p) matrix of principal component loadings
D	- (p x p) diagonal matrix of sample eigenvalues of R
R	- (p x p) matrix of correlations among the variables
A	- (p x p) matrix of column normalized eigenvectors of R

Mather (1976)

The sample used to compute the "reference" principal components loadings matrix was a sample used within this study from "Zone" 10 of the Calvert Formation. This sample was selected from visual comparisons of computer plotted outlines of all the samples, on the basis that it contained (numerous genera consisting of) a wide range of shapes representative of the majority of those encountered in succeeding samples. In actuality, any sample could have been used to produce the "reference" component loadings matrix as long as the same "reference" matrix was used in all succeeding analyses.

4.3.3 K-MEANS CLUSTER ANALYSIS

Multiple discriminant analysis (MDA) of the 6 principal component scores is used as an identification method, essentially to group similar shapes together. To implement MDA of any data set an a priori knowledge of group membership is necessary. Therefore cluster analysis, a classification technique, must be applied first to the principal component scores of a standard or reference sample. This establishes both the number of groups and their membership upon which future discriminant analyses will be based.

Initially this step involved compiling a reference sample consisting of a broad spectrum of foraminiferal shapes encountered in all of the samples. A reference sample of 500 foraminiferal shapes, represented by their respective 36 rotated radial lengths, was compiled from approximately 30 shapes per sample believed to be representative of those encountered within each sample. K-Means cluster analysis, using BMDP program KM (Dixon, 1983), of the principal components scores matrix of this reference sample was used to cluster these shapes into a manageable number of groups upon which further comparisons could be based.

Cluster analysis is a multivariate statistical classification method used to place objects (shapes) into relatively homogeneous and distinct groups im such a manner that their interrelationships are revealed. K-Means cluster analysis is an arbitrary origin method which operates on the similarity between the observations and a set of arbitrary starting points (Davis, 1986). In k-means cluster anlysis, 'k' points characterized by 'm' variables are designated by the program as initial "centroids". A matrix of simularities between the 'k' centroids and the 'n' observations is calculated and the closest or most similar observations are clustered with the nearest centroids. Observations are iteratively added to the nearest cluster, whose centroid is then recalculated for the expanded cluster (Davis, 1986). Few if any statistical tests or theory have been developed or applied to cluster analysis and due to the large number of clustering techniques and options within, it is hard to judge the utility or results of any procedure. Generally, the combination that produces the most satisfactory results is utilized. While this leads to a trial and error approach, it is thought to produce the best results.

The results of the cluster analysis were judged on two principles: first, the consistency of shapes within a cluster and distinct differences (non-overlapping) between clusters based on comparisons using computer generated plots of the foraminiferal outlines; and second, the percentage of groups correctly classified as determined by a succeeding stepwise multiple discriminant analysis of the matrix of principal component scores and cluster designations.

Initially, complete linkage hierarchical cluster analysis was used but comparisons of results with plots of the foraminiferal outlines showed sub-optimal clustering of several groups. This was futher exemplified by subsequent stepwise discriminant analysis, program BMDP7M (Dixon, 1983), of the original data matrix (principal component scores) with each cluster designation. BMDP7M lists the percent of each group correctly classified based upon the computed discriminant functions. The percent of groups correctly classified varied but contained several groups in the fifty percentile range. K-Means clustering was tried as an alternative clustering method. An option of BMDPKM is that it allows the user to specify the number of centroids or clusters. The number of pre-determined clusters was varied until 32 groups (clusters) were determined to accurately represent the reference sample shapes based on both visual and statistical comparisons. K-Means cluster analysis correctly classified 30 of 32 groups in the upper 90 percentile range (22 groups 100% correctly classified) as determined by stepwise MDA. The remaining two groups were in the 80 percentile range and although still very high, were lower because of their small size (e. g. 4 of 5 correctly classified = 80%).

4.3.4 MULTIPLE DISCRIMINANT ANALYSIS

Multiple discriminant analysis finds the linear combination of the variables (principal component scores) which produces the maximum difference between the previously defined groups. A function that produces a significant difference, can then be used to allocate samples of unknown origin to one of the original groups. K-Means cluster analysis of a compiled reference sample defined 32 groups. MDA, using a program from Mather (1976), of the reference sample principal component scores matrix with each observation's cluster designation produced a 'p' x 'p' matrix of coefficients of the discriminant functions along with a 'n' x 'p' matrix of mean discriminant scores for each of the 32 groups evaluated at each variable. These matrices are used in succeeding MDA of each sample to classify all unclassified cases into one of the 32 groups. From these results, sample to sample comparisons are based.

4.3.5 GRAPHICAL COMPARISONS

Multiple discriminant analysis of all sample sets classified each foraminiferal shape per sample into one of 32 possible morpho-groups. From these results, the percentage of each morpho-group present within a sample was calculated. The relative percentages of all 32 morpho-groups per sample were then graphed. Visual comparison of these graphs was used as a tool for both discrimination and correlation of samples (see Appendix A).

The total or accumulated percentages of four major morpho-groups per sample were also calculated. These values are simply the summation of the relative percentages of the respective morpho-groups contained within each major morpho-group. Graphical comparison of the accumulated percentages of four major morpho-groups illustrated large-scale shape trends. These results are presented in Appendix C.

4.3.6 Q-MODE CLUSTER ANALYSIS

Statistical comparison of the total or accumulated percentages of four major morpho-groups per sample was accomplished by Q-mode cluster analysis. Q-mode cluster analysis, using SPSS^{X} program Cluster, of the four major morpho-groups percentage data was performed using Ward's method of cluster linkage. Prior to the analysis, a data transformation was necessary such that observations were recorded in percent of the maximum value of that variable observed over all the samples, in an effort to avoid closed data arrays (the 4 accumulated percentages would sum to 100).

Ward's cluster linkage method (also called minimum variance) is a hierarchical clustering method which utilizes the idea that a clustering procedure should maximize internal homogeneity. This technique minimizes the the pooled within-group sums of squares (the sum of the squared distances from each point to its cluster center) at each level (Mather, 1976). Simply stated, "the two groups to be combined at any given level are those whose fusion produces the least increase in the within-group sum of squares" (Mather, 1976). Ward's method facilitates the linkage of small, close clusters. Results from Q-mode cluster analysis of the four major morpho-groups were compared to trends observed from graphical methods.

CHAPTER 5

RESULTS

5.1 PRINCIPAL COMPONENTS ANALYSIS

Principal components analysis (PCA) of rotated radial length (RRL) data was used to produce a significant reduction in the data (from 36 RRL to 6 component scores) without an appreciable loss of information. Six principal component scores were produced, accounting for 88% of the variance in the original data. These six new variables serve as adequate shape descriptors. The underlying significance of each principal component and its relative contribution to the original foraminiferal shape, although critical to a shape study, is not easily ascertained. This is because there is not a simple linear relationship between a principal component score and the portion of shape that it represents. An attempt to unravel the meaning or relationship of each principal component to that of the original shape led to a closer examination of the principal component loadings matrix.

The principal component loadings quantify the contribution of each variable to the principal component scores. A computer-generated plot of the principal component loadings matrix (Figure 5-1) gives a visual representation of the principal component loading patterns. Each principal component loading displays a distinct shape pattern which is specific only to the data set to which the PCA was applied. The loading patterns resemble "bladed propellors", where each successive loading

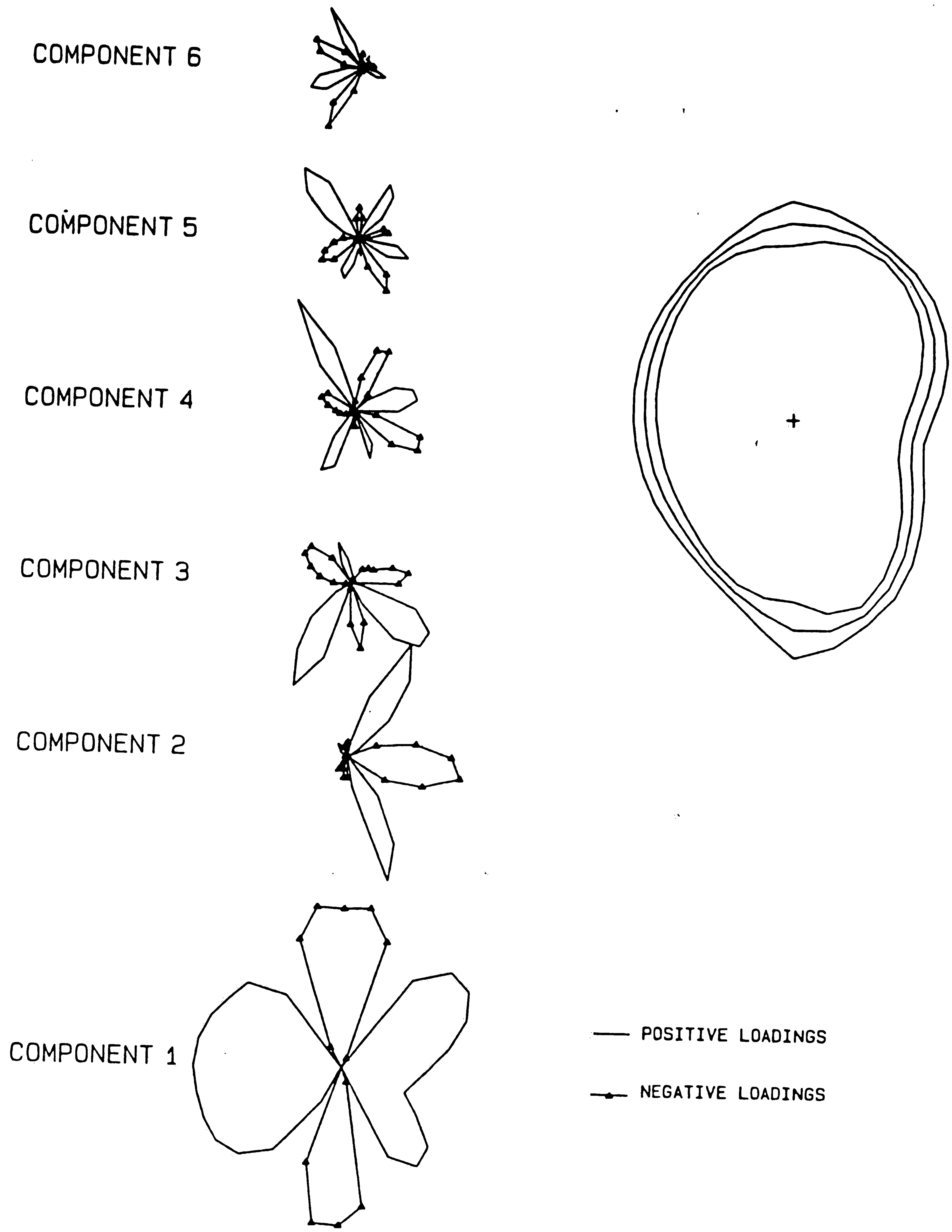


Figure 5-1: Principal component loading patterns and average shape derived from the reference sample (CS510). The outer and inner outlines of the average shape represent plus or minus one standard deviation, respectively.

accounts for a different portion of the original shape. By comparing the component loading patterns to the average shape of the sample set from which the loadings were derived, the portion of shape that each component loading accounts for becomes more understandable. In Figure 5-1 the average shape of reference sample CS510 is plotted (middle outline) along with plus or minus one standard deviation of the average shape (the outer and inner outlines, respectively).

Several distinctive aspects of the principal component loading patterns should be noted:

1. Each principal component loading pattern consists of an equal number of alternating positive and negative lobes generally in different orientations;

2. The lobes are asymmetric because they are constructed from asymmetric foraminiferal outlines;

3. Generally, the number of blades or lobes gradually increase with higher number component loadings (exceptions do occur with data sets containing a large diversity of shapes);

4. The absolute value of the component loadings gradually decrease with higher number component loadings as they account for a smaller portion of total shape variability. This is indicated by the decreasing size of the component loading patterns;

5. The relationship between a component loading and the portion of shape that it represents becomes increasingly complex with higher number components as they account for less of the total shape variability. This is particularly evident from the loading patterns (Figure 5-1). High negative loadings on component 1 represent a shape elongation in the N-S direction and high positive loadings indicate an elongation in an E-W orientation. Yet, the significance of component 2 loadings and higher are not as easily ascertained.

5.2 K-MEANS CLUSTER ANALYSIS

K-Means cluster analysis of a compiled "reference" sample classified the original data matrix into 32 groups or clusters. These 32 groups were identified from a sample of 500 foraminiferal shapes (each represented by 6 principal component scores) felt to adequately represent the spectrum of shapes encountered within all samples. K-Means cluster analysis was found to be the most effective method of classifying the reference sample. This method allows the operator to specify the number of clusters in the analysis. Thirty-two groups were attained on the basis of two criteria: visual comparison of shapes within a cluster for simularities and between clusters for differences (using computer generated plots of the foraminiferal outlines); and results from MDA indicating the percentage of cases correctly classified based upon the discriminant analysis.

A visual representation of the 32 morphological groups (clusters) was sought as an interpretive tool. This was accomplished by averaging the 36 RRL per foram of all shapes contained within each respective morpho-group. The average shape of each morpo-group was then plotted. These are illustrated in Figure 5-2. The plotted outlines of the 32 morpho-groups verified their significance, illustrating each one's distinct differences as well as showing several loosely based shape continuums. This was further illustrated by rearranging the 32 morpho-groups into an orderly progression of similar shapes (Figure 5-3).

5.3 MULTIPLE DISCRIMINANT ANALYSIS

Once the visual significance of the 32 morpho-groups had been.

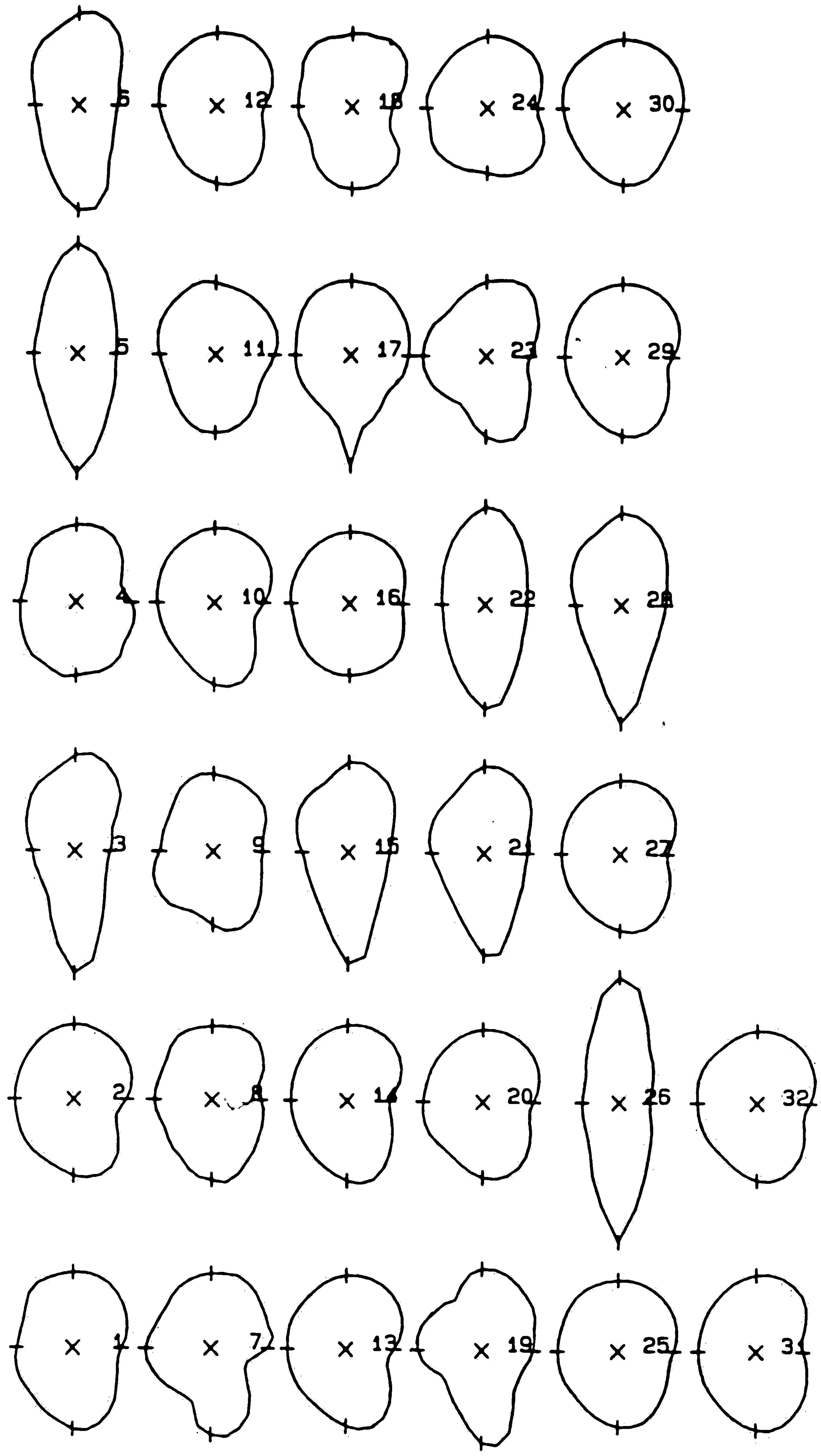


Figure 5-2: Thirty-two morphological groups. Original order determined by cluster analysis.

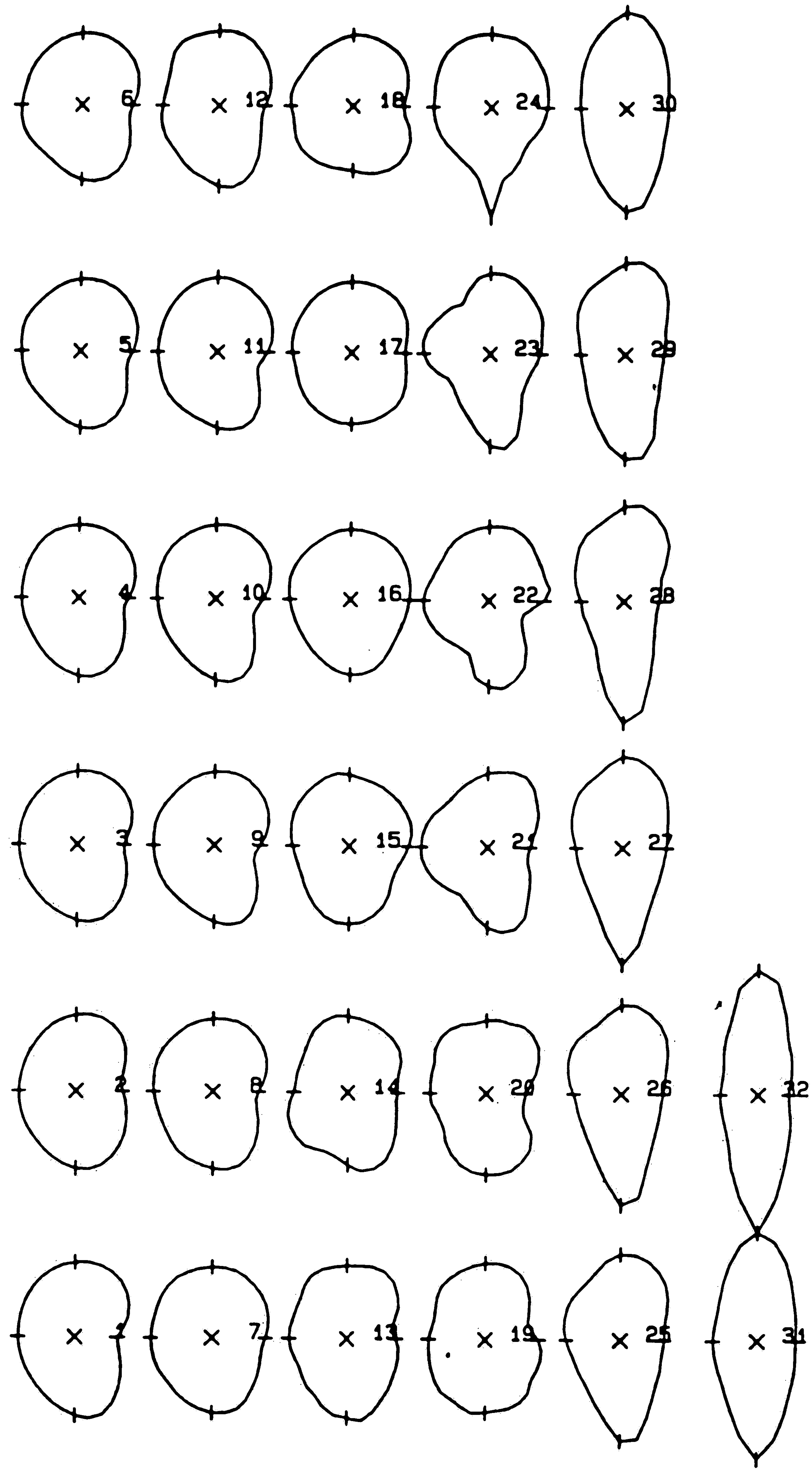


Figure 5-3: Thirty-two morphological groups. Rearranged to reflect shape continuums.

established, it was necessary to classify every foraminiferal shape within all the samples into one of the predetermined 32 morpho-groups so harmonious comparisons between samples could be made. Multiple discriminant anlaysis (MDA) applied initially to a reference sample and then to all sample sets accomplished this feat. MDA of the classified "reference" sample produced a 'p' x 'p' matrix of coefficients of the discriminant functions and a 'n' x 'p' matrix of mean discriminant scores for all morpho-groups evaluated at each variable. These were then used in succeeding MDA of each sample to classify the unclassified cases (shapes) into the closest morpho-group.

Based on these results, the relative percent of each morpho-group present within a sample could be calculated. The relative percentages of the 32 morpho-groups present within each sample were graphed and sample results were overlain for visual comparison. The results were quite striking. Samples CS709 and CW209 from Shattuck's "Zone" 9 of the Calvert Formation show very similar trends (Figure 5-4) indicative of a high correlation of morpho-group relative abundances between samples. Sample CW209, collected from the cliffs just north of Willows Beach is located approximately 5 km (3 miles) down dip from sample CS709, collected between Chesapeake Beach and Randle Cliff. Two samples from "Zone" 10 of the Calvert Formation, CS510 and CL210, also display a strong correlation to one another based on the relative proportion of 32 morpho-groups (Figure 5-5). What makes this relationship even more interesting is a distance of approximately 22 km (13.5 miles) along

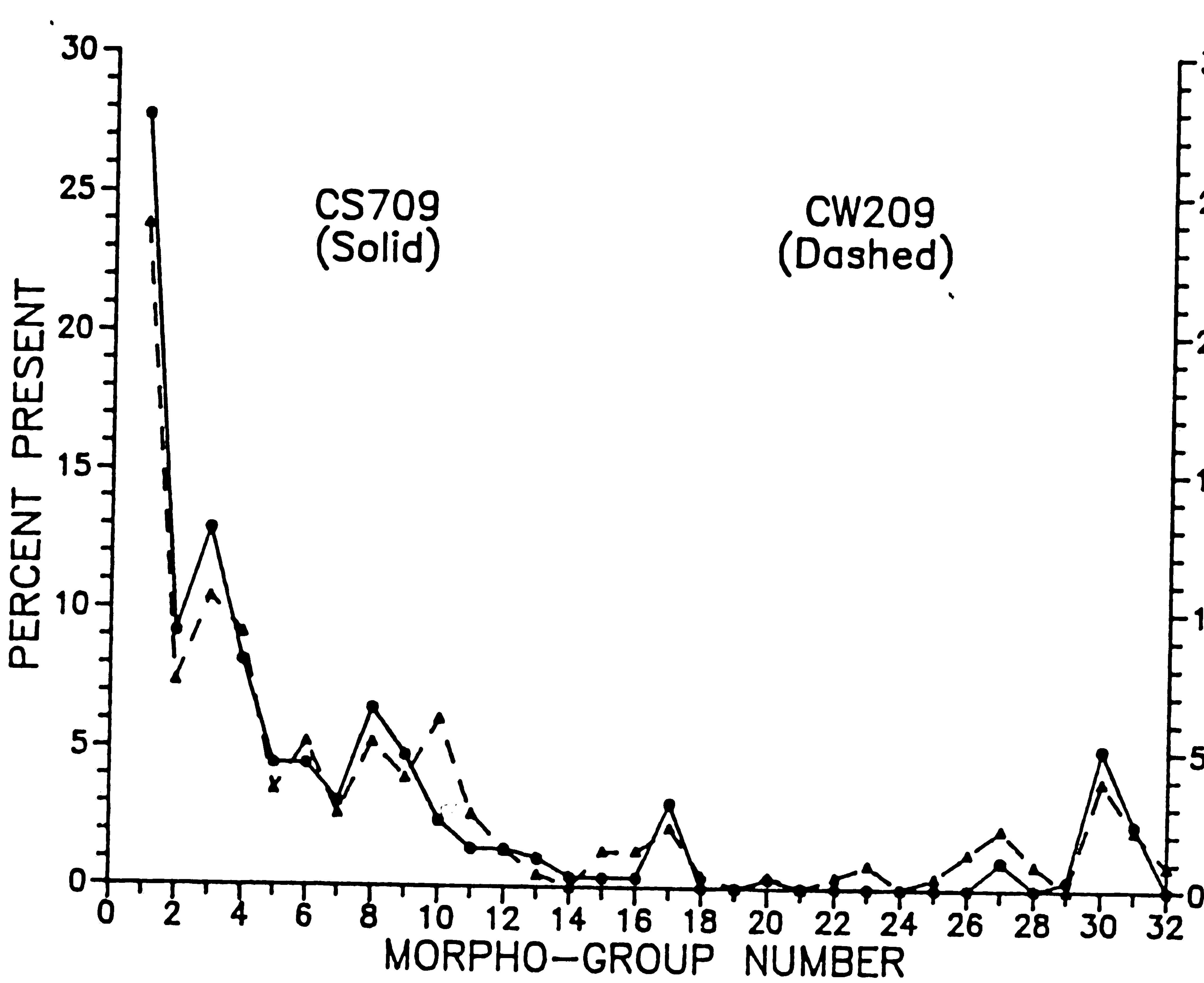


Figure 5-4: Graph of the percentages of 32 morpho-groups present within two samples from "Zone" 9.

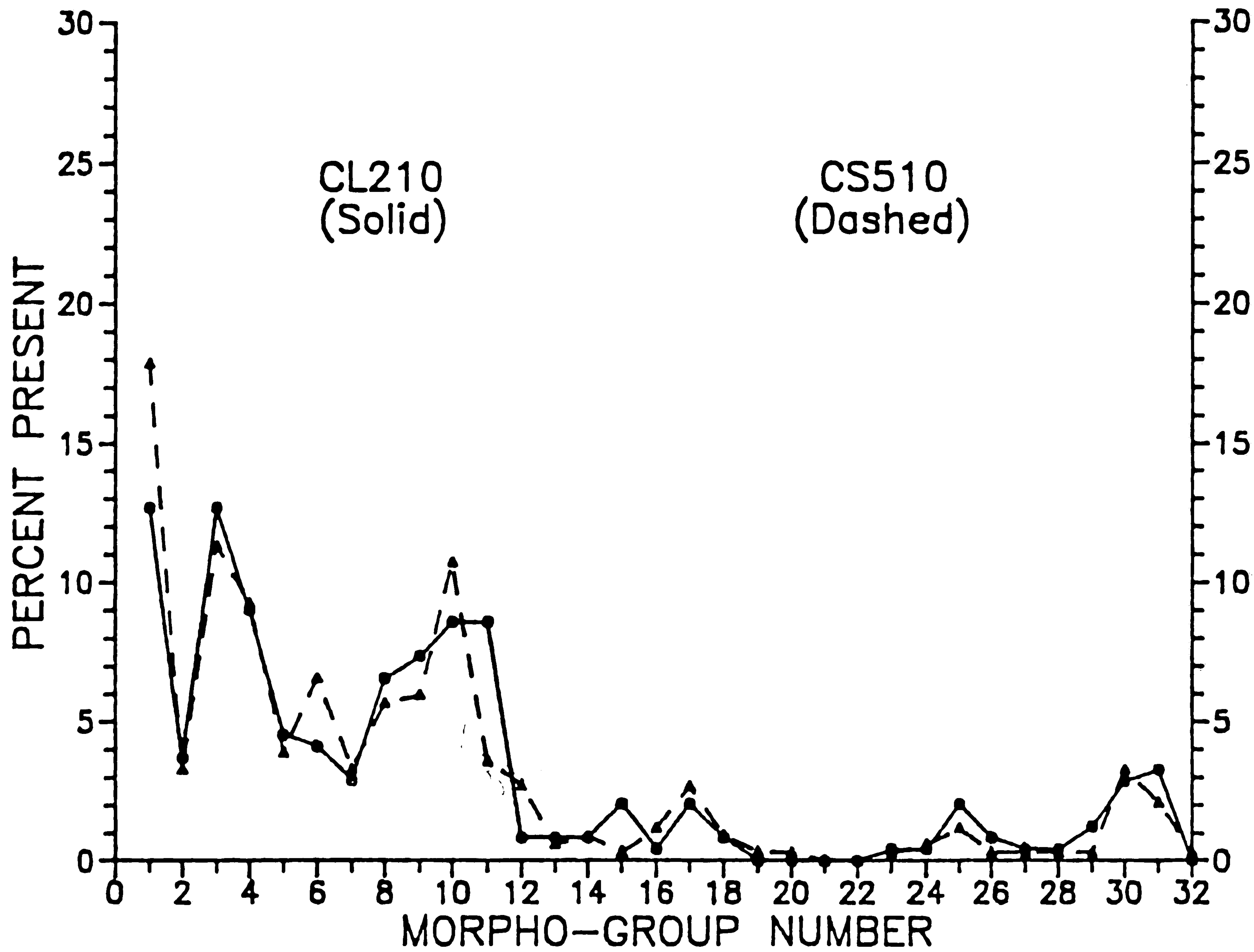


Figure 5-5: Graph of the percentages of 32 morpho-groups present within two samples from "Zone" 10.

strike separates these two. Sample CS510 was collected just north of Randle Cliff and CL210 came from an inland exposure south of the town of Aquasco.

These two samples illustrate a very important concept, the ability to correlate samples from similar stratigraphic levels both down dip and along strike regardless of local geographical separation based exclusively on the shape distributions of the entire benthic foraminifera fauna. Also evident from graphs of the 32 morpho-groups is that in general, there are distinct differences between "Zones". Samples that do show affinities of another "Zone" based upon visual comparisons, are at most one "Zone" apart (see Appendix A). This suggests that whatever controls the distribution of foraminiferal shapes operating at this level is gradualistic.

5.4 FOUR MAJOR MORPHOLOGICAL GROUPS

Visual examination of the plotted outlines of the 32 morpho-groups suggested the presence of several loosely based shape continuums. Closer inspection led to the identification of 4 major morphological groups. These are bean shaped (group 1-13), polygonal (group 14-18), bulbous (group 19-24) and elongate morpho-groups (group 25-32). See Figure 5-6 (bean shaped morpho-groups), Figure 5-7 (polygonal morpho-groups), Figure 5-8 (bulbous morpho-groups) and Figure 5-9 (elongate morpho-groups). Total or accumulated percentages of the morpho-groups residing within each of 4 agglomerated major morpho-groups was used as a basis for

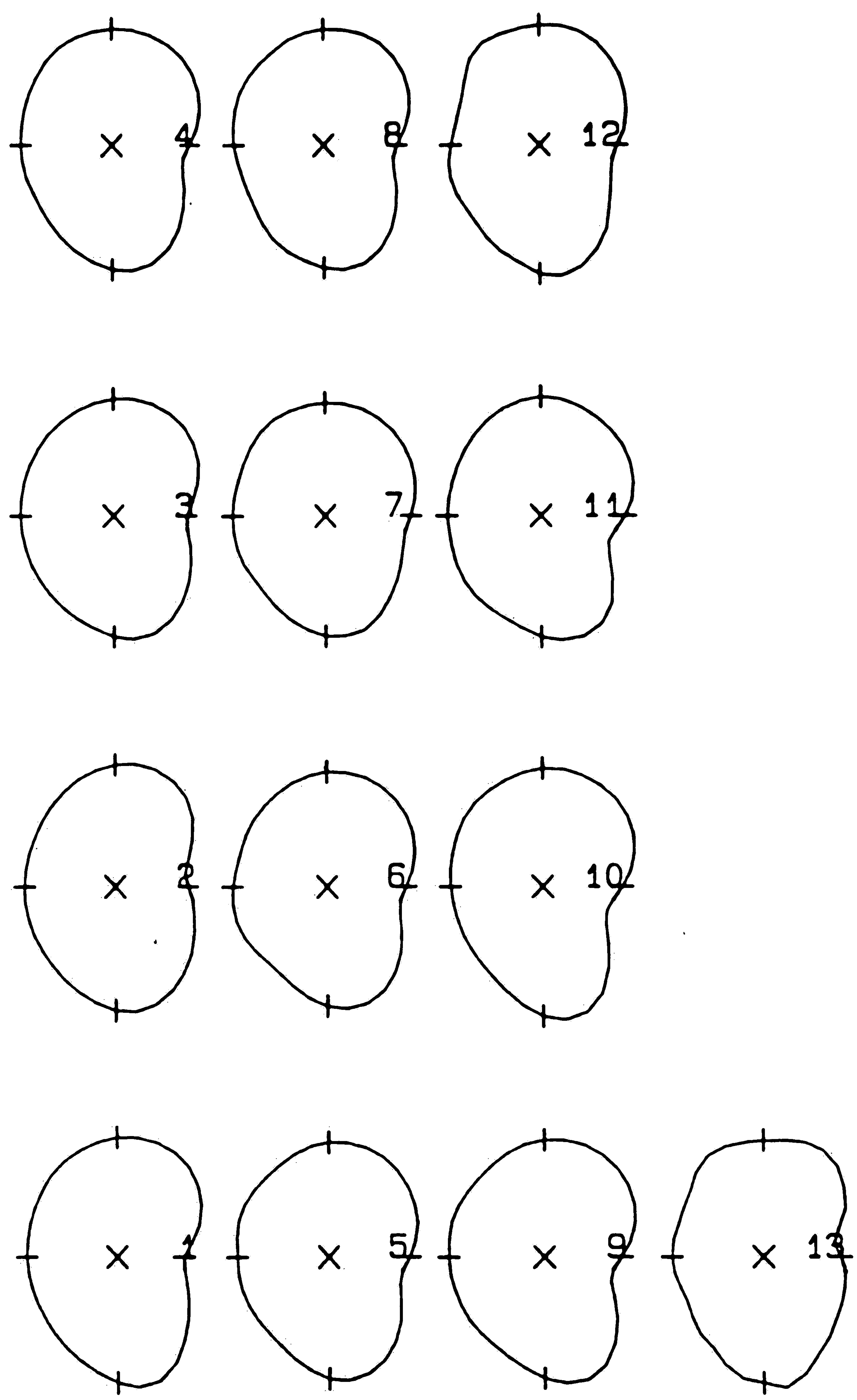


Figure 5-6: Bean shaped morphological groups.

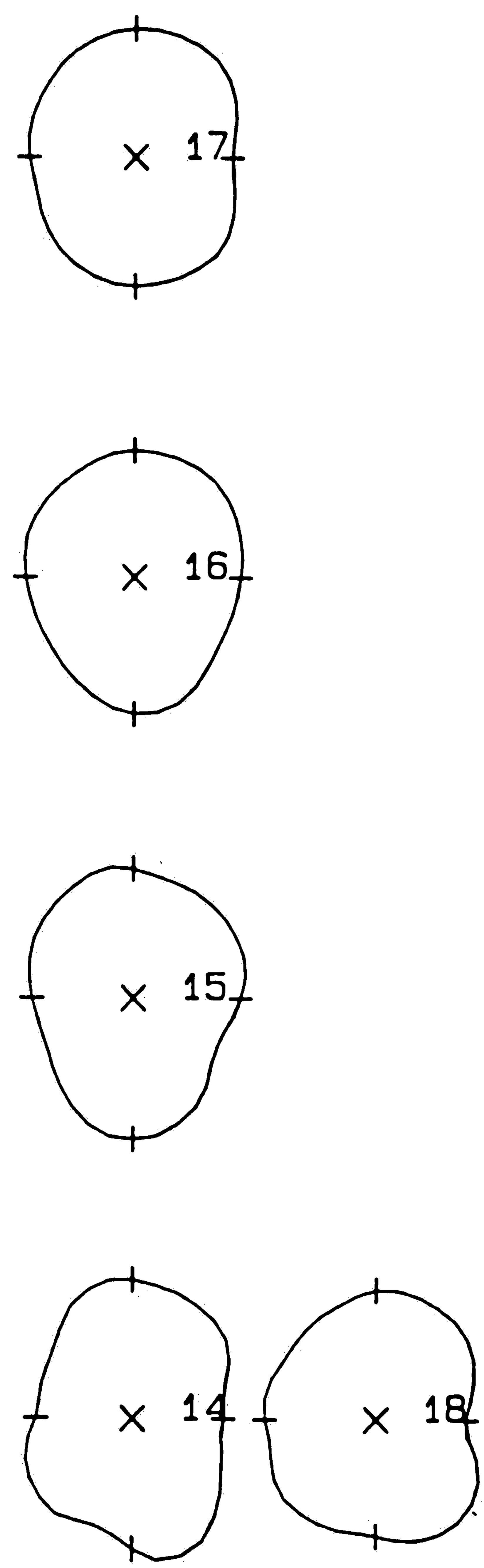


Figure 5-7: Polygonal morphological groups.

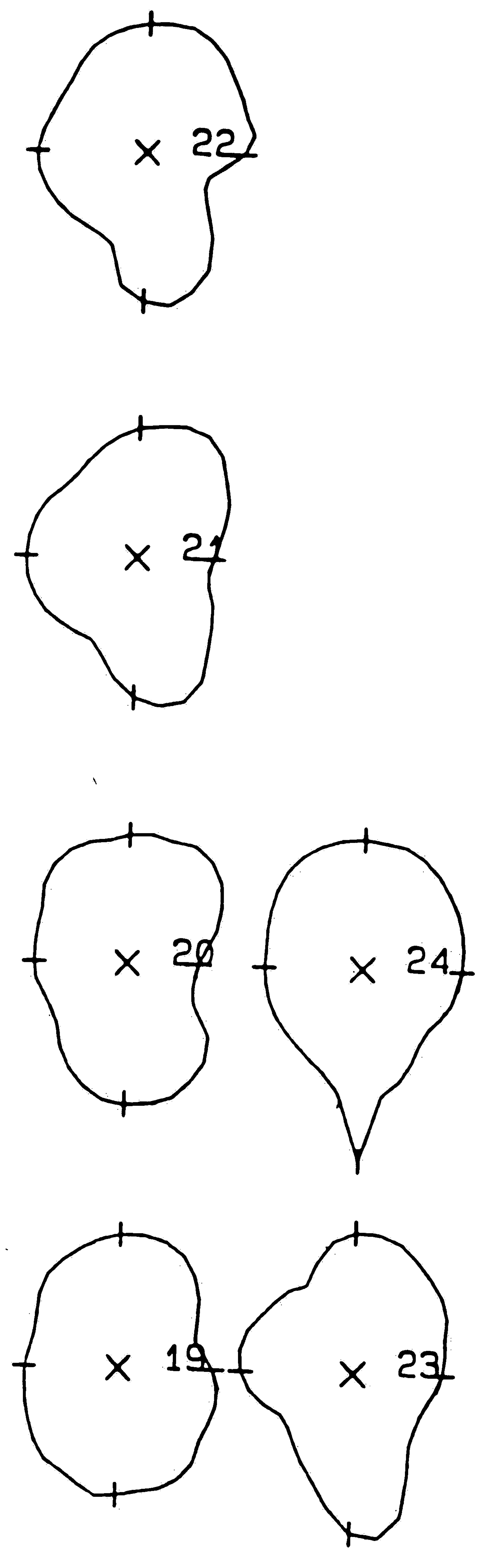


Figure 5-8: Bulbous morphological groups.

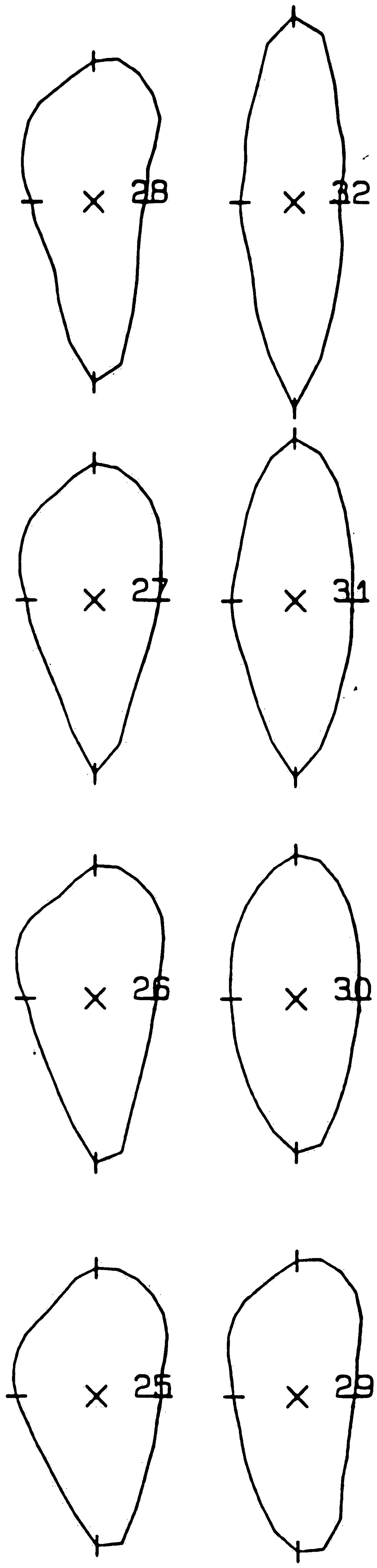


Figure 5-9: Elongate morphological groups.

comparison between different stratigraphic intervals ("Zones").

The four major morpho-groups indicated several interesting trends. There is a distinct decrease in the accumulated percent of bean-shaped morpho-groups upsection. This trend continues throughout the Calvert (Plum Point and Calvert Beach Members) and Choptank Formations. It peaks in sample CS205 ("Zone" 5) near the base of the Plum Point Member at 90.4% and steadily decreases throughout the member (see Appendix B) from 86.6% in CW308 ("Zone" 8), 82.0% in CL210 ("Zone" 10) to 74.4% in CP312 ("Zone" 12). These values continue to decrease upsection through the Calvert Beach Member, in sample CE514 ("Zone" 14) at 69.2% to 52.7% in sample CM716 ("Zone" 16), and into the Choptank Formation from 55.5% in sample CN817 ("Zone" 17) to the lowest value, in CM119 ("Zone" 19), of 42.5% at the top of the Choptank Formation.

An opposite, although more gradual, trend is exhibited by the elongate morpho-groups. These values range from 2.0% in sample CS205 upsection to 19.7% in sample CP312 of the Plum Point Member. Samples CS104 and CW506 ("Zones" 4 & 6 respectively) near the base of this member are noticeable exceptions to the aforementioned trend with anomalously high values of 14.1% and 20.7%, respectively. The elongate morpho-group values peak in the base of the Calvert Beach Member of the Calvert Formation and level off throughout the Choptank Formation with values ranging from 26.8% to 21.3% (Appendix B). The contribution of both polygonal and bulbous morpho-groups in the Plum Point Member are relatively insignificant with percentages ranging from 1.6 to 6.5 and 0.0

to 1.7, respectively. Again, samples CS104 and CW506 are noteable exceptions, containing 13.7% and 14.2% of polygonal and 4.8% and 2.3% of bulbous morpho-groups, respectively. The combined contribution of both polygonal and bulbous morpho-groups increases significantly within the upper Calvert Formation and through the Choptank Formation from 4.0% in the lower Calvert Beach Member (sample CE514 -"Zone" 14), 22.1% in the upper Calvert Beach Member, 23.1% in the lower Choptank, Drumcliff Member (CN817) to 32.9% in the upper Choptank, Boston Cliffs Member (CM119). All trends exhibited by the four major morpho-groups evolve gradually and generally cross both member and formational boundaries. Graphical representation of the 4 major morpho-group percentages and associated trends are presented in Appendix C.

Q-mode cluster analysis, the clustering of cases, was performed on the 4 major morpho-group percentage data to shed some light on sample relationships. Using accumulated percentages as variables in the cluster analysis is questionable because they are closed data arrays — the four major morpho-group percentages add up to 100 percent. Therefore, the data were transformed such that observations (32 morpho-groups) were recorded in percent of the maximum value of that variable observed over all the samples.

Results from a cluster analysis are presented in a dendrogram, or tree diagram, where cases linked at the smallest distances (lowest values of the distance function) are the most similar and those linked at progressively higher levels become increasingly dissimilar. Results of the Q-mode cluster analysis of the four major morpho-groups (Figure 5-10) support the trends illustrated by graphical means. Using a distance of 6 as a cutoff point (see Figure 5-10), 4 clusters were identified. The first cluster contains samples from "Zones" 5, 8, 9 (2 samples) and 10 (2 samples) of the Plum Point Member. The second cluster groups samples from "Zones" 11, 12 and 13 of the Plum Point Member and "Zone" 14 of the lower Calvert Beach Member. The third cluster contains samples from "Zones" 4 and 6 at or near the base of the Plum Point Member. The last cluster contains one sample from "Zone" 16 of the upper Calvert Beach Member and samples from "Zones" 17 and 19 of the overlying Choptank Formation. This analysis further illustrates the gradualistic trend upsection through the Plum Point and Calvert Beach Members of the Calvert Formation continuing through the Drumcliff and Boston Cliffs Members of the Choptank Formation. It also establishes the unique aspects of samples CS104 and CW506, attesting to their somewhat anomalous values.

```
                     RESCALED DISTANCE CLUSTER COMBINE

  C A S E      0         5        10        15        20        25
LABEL    SEQ   +---------+---------+---------+---------+---------+

CW308     4     -I
CS709     5     -I-I
CW209     6     -I I
CL210     7     -I I-------------I
CS510     8     -I I             I
CS205     2     ---I             I
                                 I-------------------------------I
CE111     9     -I               I                               I
CE313    11     -I-----I         I                               I
CP312    10     -I     I---------I                               I
CE514    12     -------I                                         I
                                                                 I
CS104     1     -----I-------I                                   I
CW506     3     -----I       I                                   I
                             I-----------------------------------I
CM716    13     ---I-----I   I
CN817    14     ---I     I---I
CM119    15     ---------I
```

Figure 5-10: Two-dimensional dendrogram illustrating results from Q-mode cluster analysis of the 4 major morphological groups.

CHAPTER 6

DISCUSSION

6.1 SUMMARY OF RESULTS

The application of a principal components analysis to harmonious two-dimensional benthic foraminiferal outlines produced 6 variables (principal component scores) which accounted for approximately 90% of the variance in the original shape data. These six shape descriptors were subjected to Q-mode cluster analysis which identified 32 clusters. These 32 clusters or morphological groups were believed to adequately characterize the variety of shapes present within all samples. Multiple discriminant analysis then classified all foraminiferal shapes in every sample into their respective morphological group. Graphical comparison of relative percentages of 32 morpho-groups from faunas taken at discrete stratigraphic levels proved valuable at correlating samples from similar stratigraphic intervals both along strike and down dip.

Four major morphological groups delineated from shape continuums of 32 morpho-groups proved to be valuable as a means of demonstrating both intra- and interformational shape trends. Graphical comparison of accumulated percentages of all morpho-groups contained within each major morpho-group established the means of distinguishing shape trends. Q-mode cluster analysis of the four major morphological groups was in agreement with graphical comparisons of different stratigraphic levels indicating a partitioning of adjacent samples due to a gradually evolving

trend toward elongated and asymmetric shapes with time.

6.2 PALEOECOLOGICAL SIGNIFICANCE

The total or accumulated percentages of the four major morphological groups indicated two major trends. The first trend is a more or less constant decrease of bean shaped morpho-groups from near the base of the Plum Point Member (90.4%) upsection through the Calvert (exclusive of the Fairhaven Member) and Choptank Formations ($\leq$55.5%). The second trend is inversely related to the first and consists of two pulses. The first pulse produces a gradual increase in the proportion of elongate morpho-groups throughout the Plum Point Member ($\geq$2.0%) into the basal Calvert Beach Member ($\leq$26.8%), after which the percentages level off. The second pulse is evident from the combined percentages of the polygonal and bulbous (asymmetric) morpho-groups. While these asymmetric morpho-groups maintain consistently low percentages in the Plum Point Member ($\leq$7.5%), they increase through the Calvert Beach Member (upper Calvert Fm.) to significant proportions in the overlying Choptank ($\geq$23.1%). These major trends are illustrated in Appendix C.

The Q-mode clustering of major morpho-group data further illustrates the gradual nature of these trends with time as it clustered samples into a near linear sequence of stratigraphic levels (Figure 5-10). The observed trends are intriguing in light of the inferred paleoecology of these deposits. In essence, the observed shape trends closely match the shallowing and slight warming trend inferred for these deposits from faunal relations of none other than the benthic foraminifera. The Calvert sediments, in general, were deposited in cool, shallow, temperate marine water with both a shallowing and slight warming trend present in the upper units. These two factors (shallow water and warmer water) are most likely related because even shallow water at the same latitude is warmer. The shallowing trend continued into the Choptank where sediments were deposited in shallower water than much of the Calvert, apparently in very shallow, cool to moderately warm water (Gibson, 1962).

The ability to correlate benthic faunas from similar stratigraphic levels along strike and down dip based on 32 morpho-group percentages established the validity of the method. By condensing the 32 morpho-groups into four major morpho-groups, intra- and interformational trends could be quantified and compared to established paleoenvironmental information. The patterns of shape variation among the entire benthic foraminiferal fauna is closely aligned with the established paleoecologic interpretations of Gibson (1962), Gernant (1970,1971) and Kidwell (1982). While the four major morpho-group percentages quite dramatically demonstrated the overall shift in environmental conditions during the middle Miocene they were not sensitive enough to detect smaller scale fluctuations of paleodepth (see Table 3-2 for comparisons, Page 21).

Any reasonable model of paleoenvironmental reconstruction has to be able to explain anomalous results. Samples CS104 and CW506 from "Zones" 4 and 6, respectively are mutually similar yet compare with samples at much higher stratigraphic levels (Calvert Beach and Drumcliff Members).

In this context these samples indicate either shallow and/or warmer water conditions than adjacent samples from near the base of the Plum Point Member. However, in light of previous discussions, these findings are either contradictory or reflect small scale fluctuations not evident in other samples. First of all, the fauna from "Zone" 4 (sample CS104) indeed may have thrived in relatively shallow water. Gernant (1971) stated that the total fauna (mollusks, ostracoda and foraminifera) of the Pyncnodote percrassa (an oyster) bed, "Zone" 4, was indicative of depths of about 25 to 30 meters. Kidwell (1982) believes that "Zone" 4 (her Ostrea facies) accumulated in shallow sublittoral depths which she defines as a "zone of frequent but noncontinuous physical reworking of the sea floor by higher energy fairweather waves, coastal currents and storm events." Indeed, sample CS104 may not be anomalous but indicative of shallow conditions that prevailed after the development of the basal unconformity on the surface of the underlying Fairhaven Member. This erosional surface apparently developed in very shallow sublittoral conditions and was favorable for the development of an oyster bioherm.

Sample CW506 from "Zone" 6 is not as easily explained. "Zones" 4-9 are interpreted as a conformable sequence with a paleodepth increase in "Zones" 5-9 to possibly 40 to 55 meters of open ocean water (Gernant, 1971). Several explanations are possible. Portions of this benthic foraminiferal fauna may be allochthonous, either the result of localized reworking of older deposits or the rafting of nearshore and likewise shallower species by current and/or wave action. This a common problem in the analysis of foraminiferal faunas. The process of contamination by human agency is always a possibility but in light of efforts made to prevent such an occurrence, it is not believed to be a viable explanation. Another interpretation is based on the variable and sometimes conflicting environmental conditions established by judgements based on different faunas. "Zone" 12 for example, a bone bed, is interpreted to have been deposited in water possibly as deep as 75 or 80 meters (Gernant, 1971) based on invertebrates. Yet Whitmore (1971), in his discussion of vertebrate remains from the studied deposits, reports numerous sea cows from "Zone" 12. The modern dugong, a close relative of the sea cow, prefers a water depth of approximately 15 feet (4.6 m). If the sea cow flourished in similar depths, a major depth discrepency exists.

Clearly evident from several workers (Gernant, 1970; Kidwell, 1982) is the existence of different litho- and biofacies within certain "Zones". Therefore, environmental determinations for an entire "Zone" based on faunal relations are biased with respect to sample location (provinciality) and the fauna studied. Whatever the cause of anomalous values from "Zone" 6, it is not felt to adversely affect the conclusions of this study.

Gibson (1962) made an interesting observation in his work on the systematic paleontology of the benthic foraminifera of the Atlantic coast middle Miocene deposits (including but not exclusive to the Calvert and Choptank Formations):

> Another interesting observation in both living and fossil Foraminifera is a unidirectional change in morphology in relation to what appears to be a unidirectional change in the environment. In many species certain characters such as the ornamentation and retral processes exhibit a definite trend in variation. On examination, this trend can be seen to be correlated either with a north-south direction along the coastline or a shallow to deep water depth. . . . As these morphologic changes are correlated with environmental changes, with no evidence of geographical separation, it is suggested that the morphologic differences are only phenotypic, resulting from differences in environmental influence upon the genotype, and not basic genetic differences.

Intraspecific variation in foraminifera can be either genetically derived or due to environmentally induced phenetic deviations. Phenotypic variation usually is related to environmental factors. These environmental factors — temperature extremes, salinity, turbidity, oxygenation and pH, substrate nature — in addition to biologic interactions with the food supply and parasites or predators influence the growth of foraminifera (Tappan, 1976). Undoubtably, many of these factors also impact the distribution of species and consequently their associated morphology. Water depth, either directly or indirectly controls many of these factors, such as temperature, turbidity, oxygenation and nature of the substrate. While water depth alone cannot account for the distribution of species and degree of intraspecific shape variation in benthic foraminifera, it may be a major controlling factor. Therefore, if morphologies are distributed systematically, then the shapes observed apparently reflect the major conditions which control their distribution — noteably paleobathymetry.

CHAPTER 7

CONCLUSIONS

A. METHOD

1. A principal axes method of rotating foraminiferal shapes to a common orientation is extremely successful in producing mutual orientations for comparison of genera and species. This may be due to an inherent growth pattern in benthic foraminifera which preserves a major axis of growth translation even in relatively "circular" forms.

2. Six principal components accounting for approximately 90% of the original sample variance are valid shape descriptors of benthic foraminifera. Subsequent analysis by a variety of multivariate statistical and graphical methods is necessary to extract the underlying significance of the components.

3. Thirty-two groups derived from cluster analysis are adequate to classify the shape variability within the entire population of foraminiferal shapes. Computation and plotting of an average shape for each of 32 morphological groups produces a visual representation of the shapes accounted for within each group.

4. Four major morphological groups — bean, polygonal, bulbous, and elongate -- consisting of distinct shape continuums are useful discriminators of intra- and interformational shape trends.

B. GEOLOGIC SIGNIFICANCE

1. Correlation of similar stratigraphic levels (same "Zone") both down dip and along strike is possible based solely on benthic foraminifera shapes, regardless of local geographic separation. Discrimination of different stratigraphic levels is also achieved on the same basis.

2. Two interrelated shape trends are present within the Calvert (exclusive of the Fairhaven Member) and Choptank Formations. The first trend consists of a steady decrease in bean shaped morphogroups upsection from near the base of the Calvert to the top of the Choptank. The second trend is inversely related to the first

and is divided into two pulses. The first pulse consists of a gradual increase of elongate morpho- groups through the Plum Point Member peaking at the base of the Calvert Beach Member. A second pulse produces a steady increase in asymmetric morpho-group (polygonal and bulbous groups combined) percentages in the upper Calvert (Calvert Beach Member) to significant proportions through the Choptank.

3. The independently determined major warming and shallowing trend present in these middle Miocene deposits is believed to be reflected in the two shape trends exhibited by the benthic foraminifera.

4. The utility of morpho-groups holds great promise in paleoenvironmental studies based on benthic foraminifera apparently due to the systematic distribution of foraminifera shapes. The application of such a method may enhance results from more conventional paleoecologic studies based on species abundances.

REFERENCES

Aycox, Tracie L., 1985, Relationship Between Morphological Variation and Environment in Holocene North Atlantic Benthic Foraminifera: Unpubl. M. S. Thesis, University of New Orleans, New Orleans, La., 59p.

Bandy, Orville L., 1964, General Correlation of Foraminiferal Structure With Environment, in Imbrie, John, and Newell, Norman, eds., Approaches to Paleoecology: John Wiley & Sons, New York, p. 75-90.

Belyea, Paul R., and Thunell, Robert C., 1984, Fourier Shape Analysis And Planktonic Foraminiferal Evolution: The Neogloboquadrina - Pulleniatina Lineages: Journal Paleotology, v. 58, p. 1026-1040.

Blackwelder, Blake W., and Ward, Lauck W., 1976, Stratigraphy of the Chesapeake Group of Maryland and Virginia: Geol. Soc. of America, NE - SE Meeting, Guidebook for Field Trip 7b, 55p.

Bookstein, F. L., Strauss, R. E., Humphries, J. M., Chernoff, B. C., Elder, R. L., and Smith, G. R., 1982, A comment upon the uses of Fourier methods in Systematics: Systematic Zoology, v. 31, p. 85-92.

Brasier, M. D., 1975, Morphology And Habitat Of Living Benthonic Foraminiferids From Carribean Carbonate Environments: Revta Esp. Micropaleont., vol. 7, no. 3, p. 567-578.

Chamney, T. P., 1976, Foraminiferal Morphogroup Symbol For Paleoenvironmental Interpretation Of Drill Cutting Samples: Arctic America, in Schafer C. T., and Pelletier, B. R., eds., First Int. Symp. on Benthonic Foraminifera of Continental Margins: Maritime Sediments Spec. Pub. No. 1, Halifax, Nova Scotia, Canada, p. 585-624.

Clark, Malcolm W., 1981, Quantitative Grain Shape Analysis: A Review: Mathematical Geology, v. 13, p. 303-320.

Clark, W. B., Shattuck, G. B., and Dall, W. H., 1904, The Miocene deposits of Maryland: Maryland Geol. Survey, Miocene Volume, 543 p.

Collins, David G., 1983, The Multivariate Rotation Method of Quantitative Shape Analysis: Unpubl. M. S. Thesis, Lehigh University, Bethlehem, Pa., 76p.

Culver, Stephen J., Gary, Anthony C., and Buzas, Martin A., 1985, Benthic Foraminiferal Morphology: New Approach to Paleodepth Interpretations in Northern Gulf of Mexico: Am. Assoc. Petrol. Geol. Bull., v. 69, no. 2, p. 247.

Davis, John C., 1973, Statistics and Data Analysis in Geology: John Wiley & Sons, New York, 550p.

-----, 1986, Statistics and Data Analysis in Geology, 2nd Edition: John Wiley & Sons, New York, 646p.

Dixon, W. J. (Chief Ed.), 1983, BMDP Statistical Software: University of California Press, Berkley, California, 733p.

Dryden, A. L., 1936, The Calvert Formation in southern Maryland: Proceedings, Penn. Academy of Science, v. 10, p. 421-51.

Ehrlich, R., and Weinberg, B., 1970, An exact method for chacterization of grain shape: Journal Sed. Petrology, v. 40, p. 205-212.

Gernant, Robert E., 1970, Paleoecology of the Choptank Formation (Miocene) of Maryland and Virginia: Maryland Geol. Survey, Rept. Investigations 12, 90p.

-----, 1971, Invertebrate Biofacies And Paleoenvironments, in Gernant, R. E., Gibson, T. G., and Whitmore, F. C., Jr., Environmental History Of Maryland Miocene: Maryland Geol. Survey, Guidebook No. 3, p. 19 -30.

Gibson, Robert G., 1985, Provenance and Stratigraphic Relationships of Cretaceous Nonmarine Sediments, Middle Atlantic Coastal Plain - An Application of Quantitative Grain Shape Analysis: Upubl. M. S. Thesis, Lehigh University, Bethlehem, Pa., 84p.

Gibson, Thomas G., 1962, Benthonic Foraminifera and Paleoecology of the Miocene Deposits of the Middle Atlantic Coastal Plain: Unpubl. Ph. D. Dissertation, Princeton University, 198p.

Glaser, John D., 1968, Coastal Plain Geology Of Southern Maryland - 9th Annual Field Conf., Atlantic Coastal Plain Geol. Assoc., Maryland Geol. Survey, Guidebook No. 1, 56p.

Glassburn, Tracy A., 1987, Principal Components Quantitative Shape Analysis of Middle Miocene Bivalves from Southern Maryland: Unpubl. M. S. Thesis, Lehigh University, Bethlehem, Pa., 168p.

Hall, J. K., 1976, Algorithms and Programs for the Rapid Computation of Area and Center of Mass: Computers & Geosciences, v. 1, p. 203-205.

Healy-Williams, Nancy, and Williams, Douglas F., 1981, Fourier analysis of test shape of plantonic foraminifera: Nature, v. 289, p. 485-487.

Kidwell, Susan M., 1982, Stratigraphy, Invertebrate Taphonomy And Depositional History Of The Calvert And Choptank Formations, Atlantic Coastal Plain: Unpubl. Ph. D. Dissertation, Yale University, New Haven, Conn., 514p.

Lohmann, G. P., 1983, Eigenshape Analysis of Microfossils: A General Morphometric Procedure for Describing Changes in Shape: Mathematical Geology, v. 15, no. 6, p. 659-672.

Malkin, Doris S., 1953, Biostratigraphic Study Of Marine Ostracoda Of New Jersey, Maryland , and Virginia: Journal of Paleontology, v. 27, no. 6, p. 761-799.

Mather, P. M., 1976, Computational Methods of Multivariate Analysis in Physical Geography: John Wiley & Sons, London, England.

Mazzullo, J. M., Ehrlich, R. and Hemming, M. A., 1984, Provenance and Areal Distribution of Late Pleistocene and Holocene Quartz Sand on the Southern New England Continental Shelf: Journal Sedimentary Petrology, v. 54, p. 1335-1348.

McLean, J. D., Jr., 1969, Miocene Paleoecology and Stratigraphy- A Semi-Automated Correlation Of Outcrop Data From The Atlantic States: Repts. McLean Paleont. Lab, No. 7, 169p.

———, 1970, A Review Of The Paleoecology Of The Choptank formation From Data By Robert E. Gernant: Repts. McLean Paleont. Lab, No. 10, p. 1 -57.

Mengel, Martin E., 1985, Computerized Two-Dimensional Shape Sieving Of Carbonate Sands Using The Multivariate Rotation Method: Unpubl. M. S. Thesis, Lehigh University, Bethlehem, Pa., 90p.

Newell, Wayne L., and Rader, Eugene K., 1982, Tectonic Control Of Cyclic Sedimentation In The Chesapeake Group Of Virginia And Maryland, in Lytle, Peter T., ed., Central Appalachian Geology, NE-SE GSA '82 Field Trip Guidebooks, Falls Church, Va.: Am. Geol. Institute, p. 1-27.

Parks, James M., 1981, Recognition of Sand Body Depositional Environments: Limitations of Fourier Analysis and New Approach to Grain Shape Analysis: Am. Assoc. Petrol. Geol. Bull., v. 65. no. 5, p. 968-969.

———, 1982, Effects of Selective Shape Sorting and Provenance on Sand Grains: Comparison to Fourier and Rotation Methods for Quantitative Shape Analysis: Int'l Assoc. Sedimentologists Meeting, Hamilton, Ontario, Canada, 1982.

———, 1983a, Eigenshape Analysis of Unconsolidated Sandstones from New Jersey and Lithified Sandstones from Pennsylvania: Geol. Soc. Am. Abstr. Prog., Northeastern Section , v. 15, no. 3, p. 127.

———, 1983b, Reference Rotated Eigenshape Analysis of Sands and Sandstones: Am. Assoc. Petrol. Geol. Bull., v. 67, no. 3, p. 529.

Pflum, C. E., and Frerichs, W. D., 1976, Gulf of Mexico Deep-Water Foraminifers: Cushman Foundation for Foraminiferal Research, Spec. Publication no. 14, p. 21-31.

Schwarcz, H. P., and Shane, K. C., 1969, Measurement Of Particle Shape By Fourier Analysis: Sedimentology, v. 13, p. 213-231.

Scott, G. H., 1975, Variation In Globorotalia Miozea (Foraminiferida) From The New Zealand Neogene: New Zealand Journal Geol. and Geophys., v. 18, p. 865-880.

———, 1976, Estimation of Ancestry in Planktonic Foraminifera: Globoquadrina Dehiscens: New Zealand Journal Geol. and Geophys., v. 19, p. 311-325.

———, 1979, The Late Miocene to Early Pliocene History of the Globorotalia Miozea Plexus From Blind River, New Zealand: Marine Micropaleotology, v. 4, p. 341-361.

———, 1980, The Value Of Outline Processing In The Biometry And Systematics Of Fossils: Paleontology, v. 23, p. 757-768.

Severin, Kenneth P., 1983, Test Morphology Of Benthonic Foraminifera As A Discriminator Of Biofacies: Marine Micropaleontology, v. 8, p. 65-76.

Shattuck, George B., 1902, The Miocene Problem of Maryland: Abstracts of Science, v. XV, no. 388, p. 906.

———, 1904, Geological and paleontological relations, with a review of earlier investigations, in Clark, W. B., Shattuck, G. B., and Dall, W. H., The Miocene deposits of Maryland: Maryland Geol. Survey, Miocene Volume, p. xxxiii-cxxxvii.

Siwiec, Steven F., 1986, The Multivariate Rotation Method of Shape Analysis as Applied to Pebbles: A Case Study from the Jackson Hole - Gros Ventre River Area, Teton County, Wyoming: Unpubl. M. S. Thesis, Lehigh University, Bethlehem, Pa., 82p.

Tappan, Helen, 1976, Systematics And The Species Concept In Benthonic

Foraminiferal Taxonomy, in Schafer, C. T., and Pelletier, B. R., eds., First Int. Symp. on Benthonic Foraminifera of Continental Margins: Maritime Sediments Spec. Publ. No. 1, Halifax, Nova Scotia, Canada, p. 301-313.

Tough, J. G., and Miles, R. G., 1984, A Method For Characterizing Polygons In Terms Of The Principal Axes, Computers & Geosciences, v. 10, no 2-3, p. 347-350.

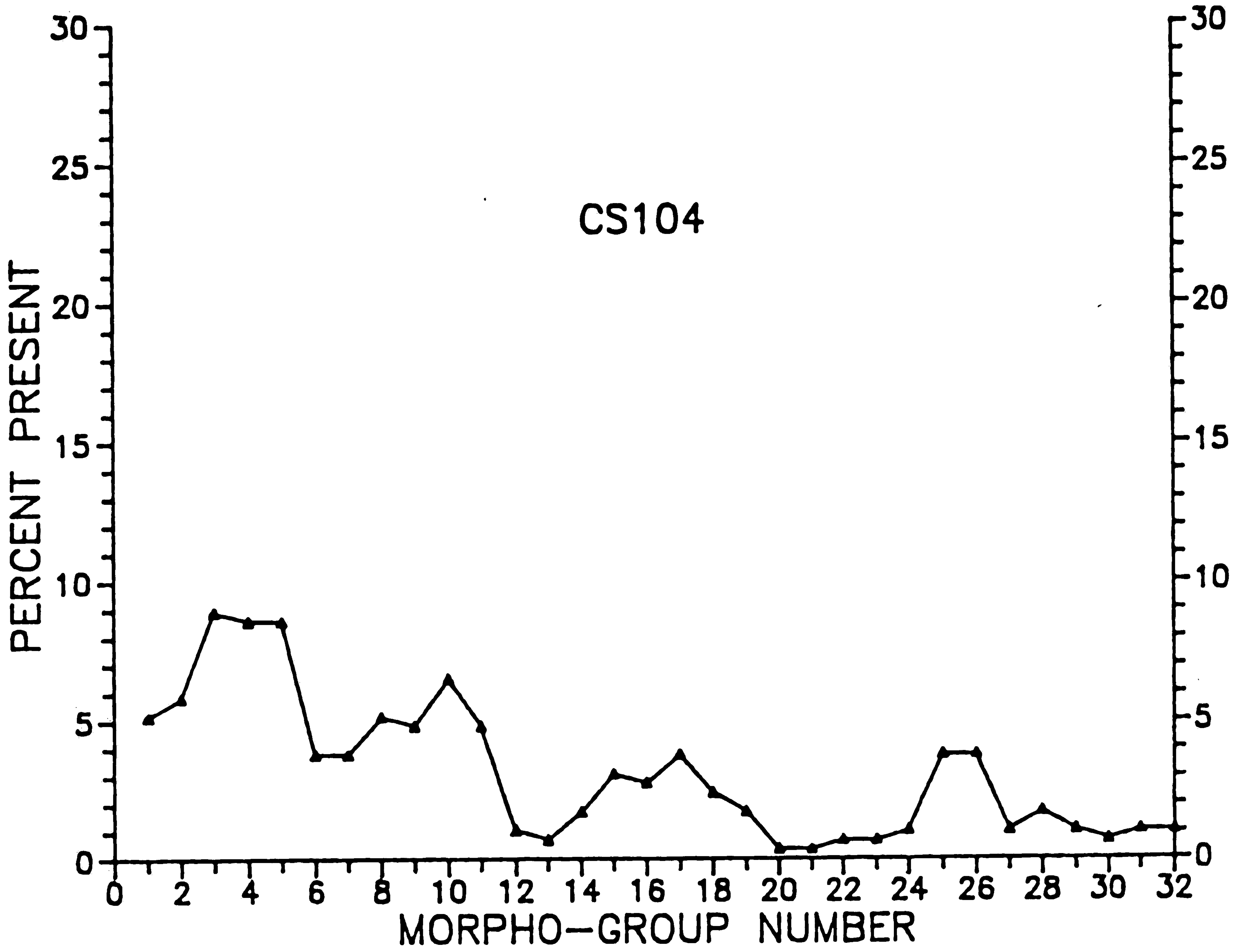
Ward, Lauck W., 1984a, Stratigraphy of Outcropping Tertiary Beds Along The Pamunkey River - Central Virginia Coastal Plain, in Ward, L. W., and Krafft, Kathleen, eds., Stratigraphy and Paleontology of the Outcropping Tertiary Beds in the Pamunkey River Region, Central Virginia Coastal Plain - Guidebook for Atlantic Coastal Plain Geol. Assoc. 1984 field trip: Atlantic Coastal Plain Assoc., p. 11-77.

-----, 1984b, Stratigraphy And Molluscan Assemblages Of The Pamunkey And Chesapeake Groups, Upper Potomac River, in Frederiksen, N. O., and Krafft, K., eds., Cretaceous and Tertiary Stratigraphy, Paleotology, and Structure, Southwestern Maryland and Northeastern Virginia: American Assoc. of Stratigraphic Palynologists Field Trip Volume and Guidebook, p. 3-77.

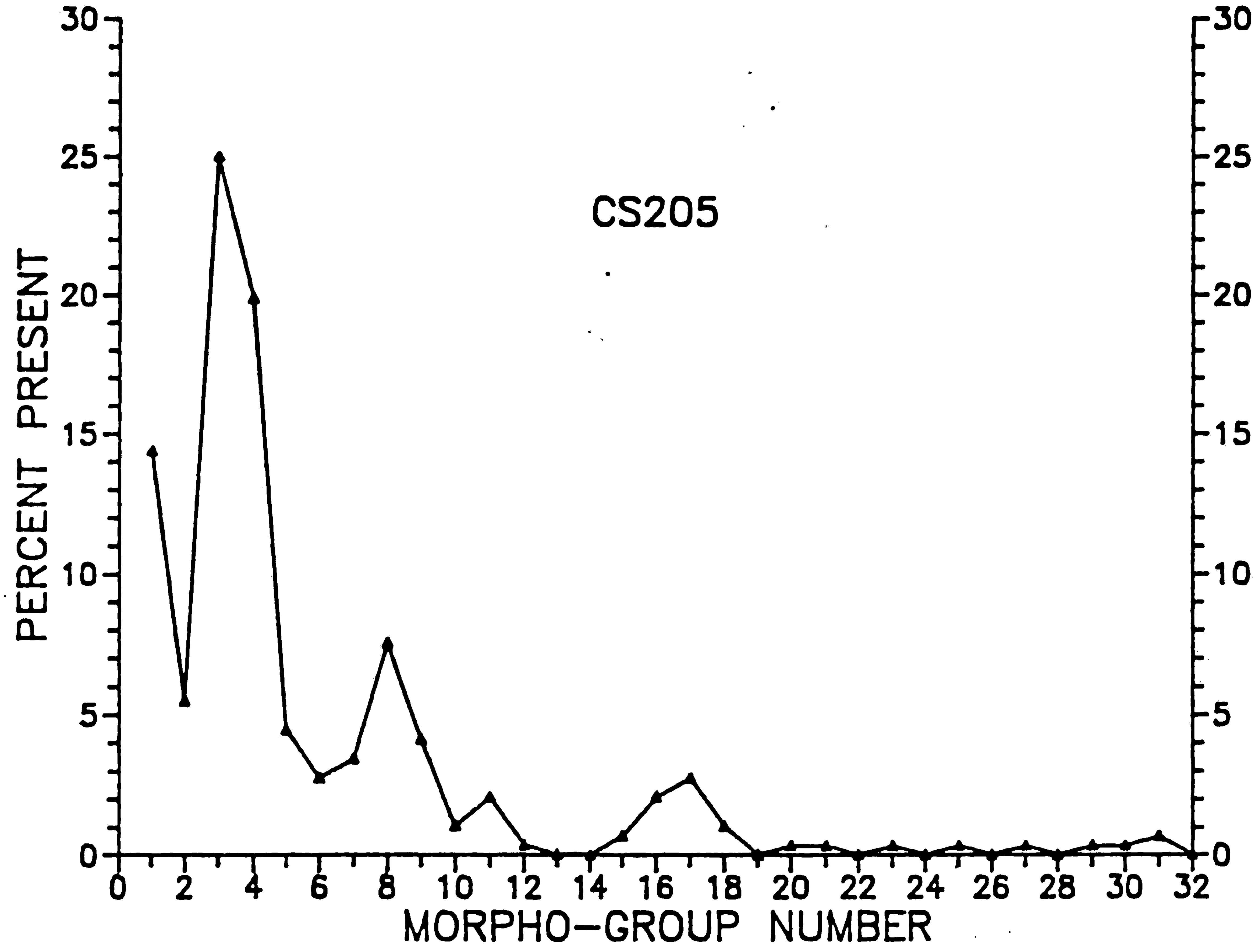
-----, 1985, Stratigraphy and Characteristic Mollusks of the Pamunkey Group (Lower Tertiary) and the Old Church Formation of the Chesapeake Group - Virginia Coastal Plain, U. S. Geol. Survey Professional Paper 1346, 78p.

Whitmore, F. C., Jr., 1971, Vertebrate Biofacies And Paleoenvironments, in Gernant, R. E., Gibson, T. G., and Whitmore, F. C., Jr., Environmental History Of Maryland Miocene: Maryland Geol. Survey, Guidebook No. 3, p. 31-36.

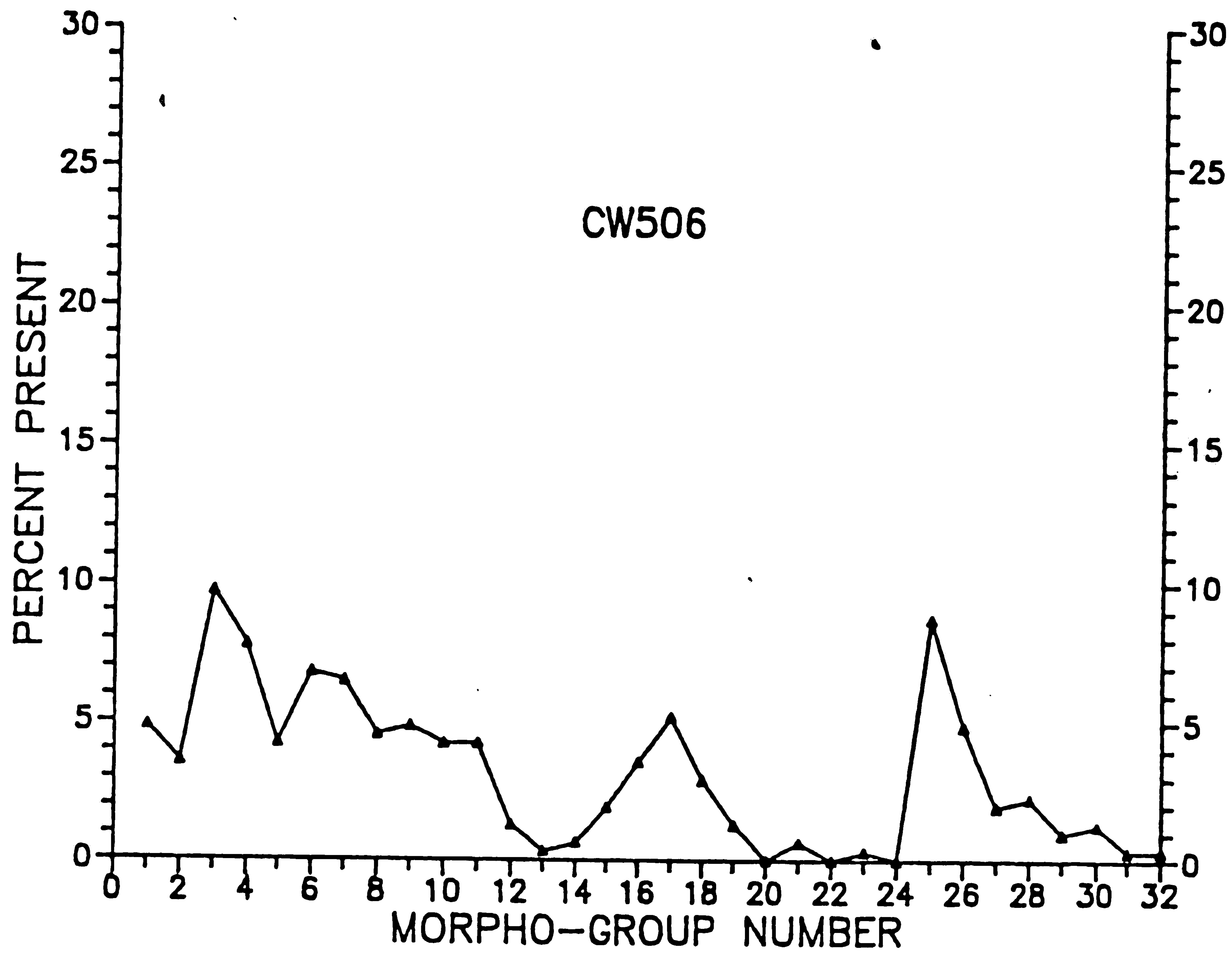
Appendix A



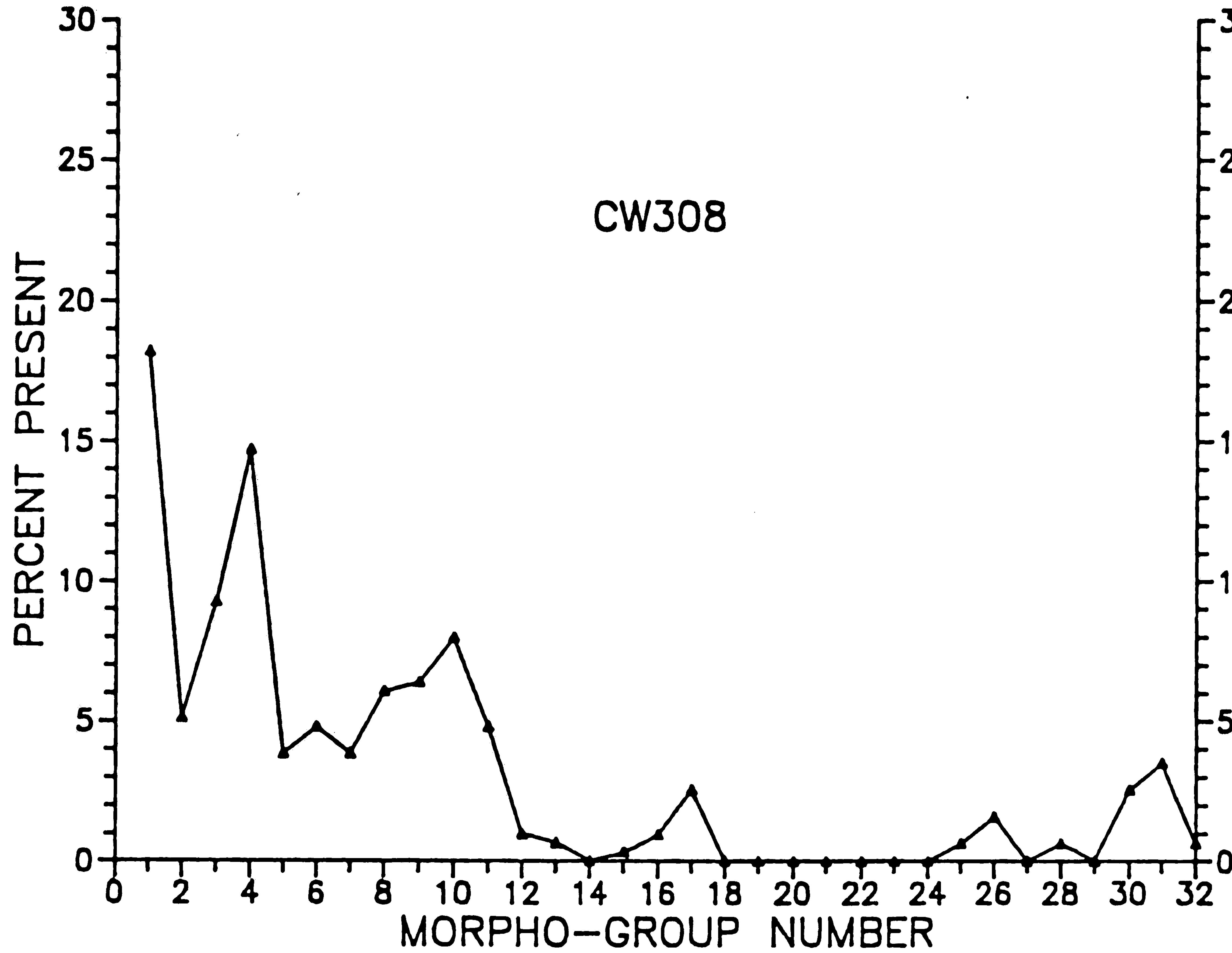
A-1: Graph of the percentages of 32 morpho-groups present within sample CS104 from "Zone" 4.



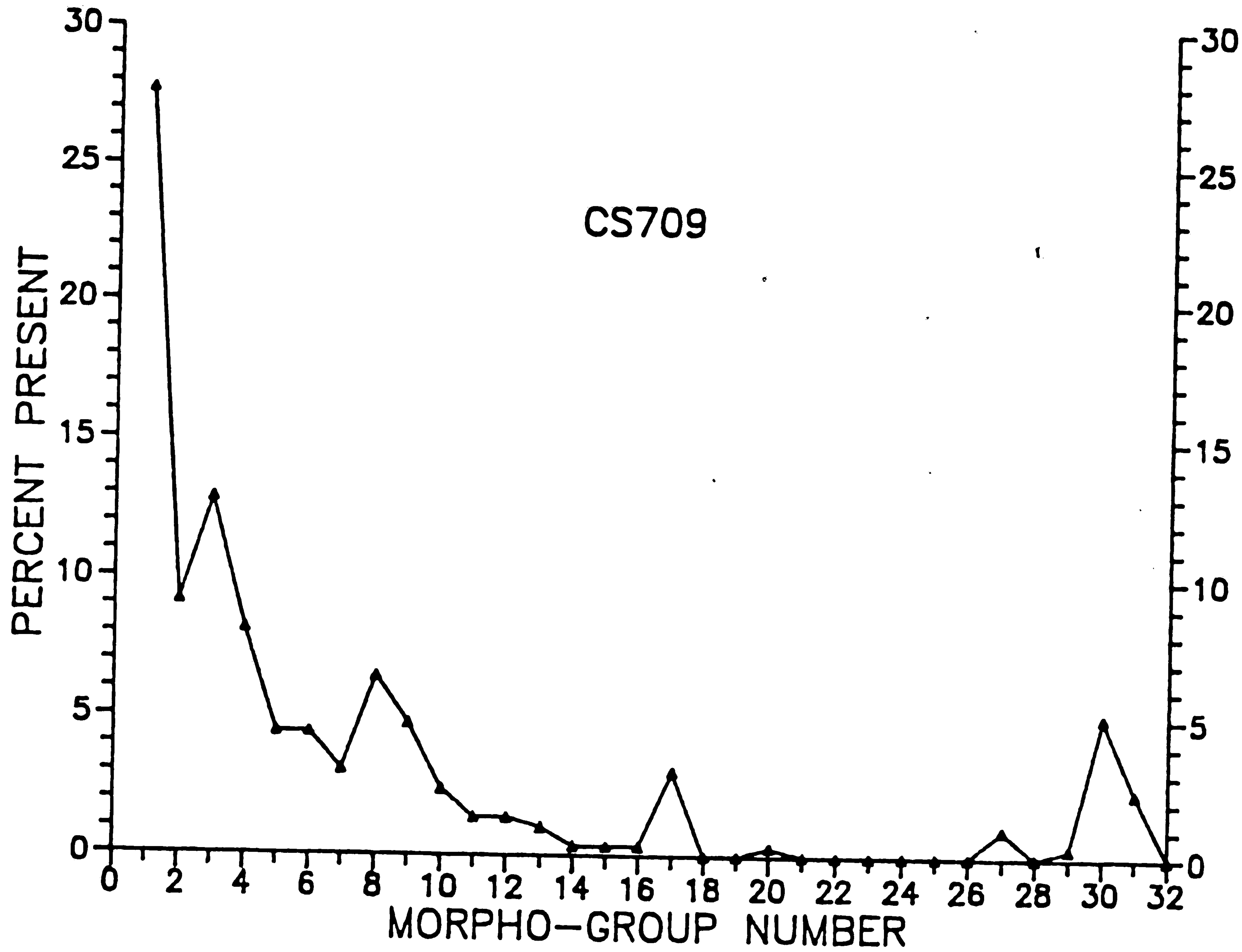
A-2: Graph of the percentages of 32 morpho-groups present within sample CS205 from "Zone" 5.



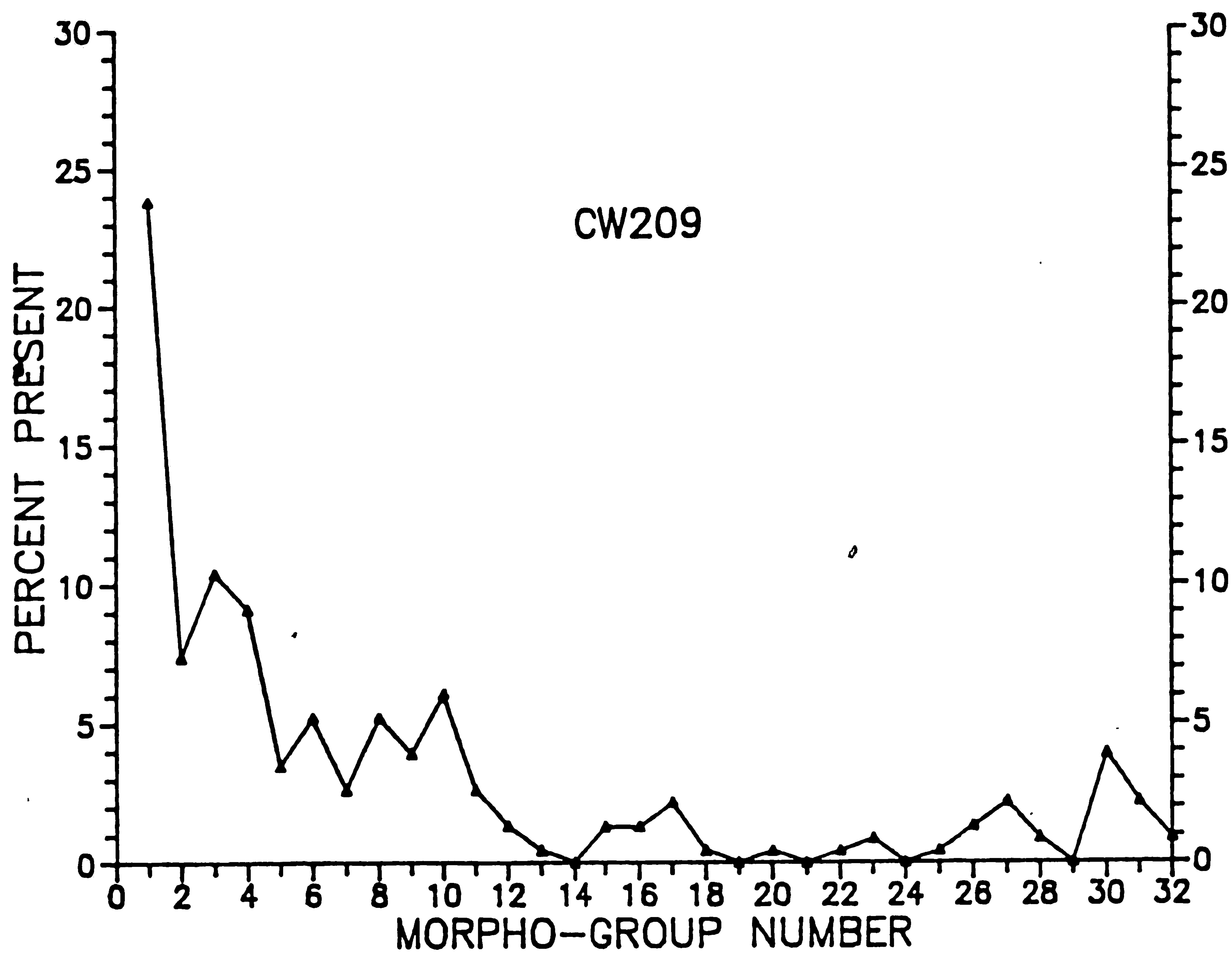
A-3: Graph of the percentages of 32 morpho-groups present within sample CW506 from "Zone" 6.



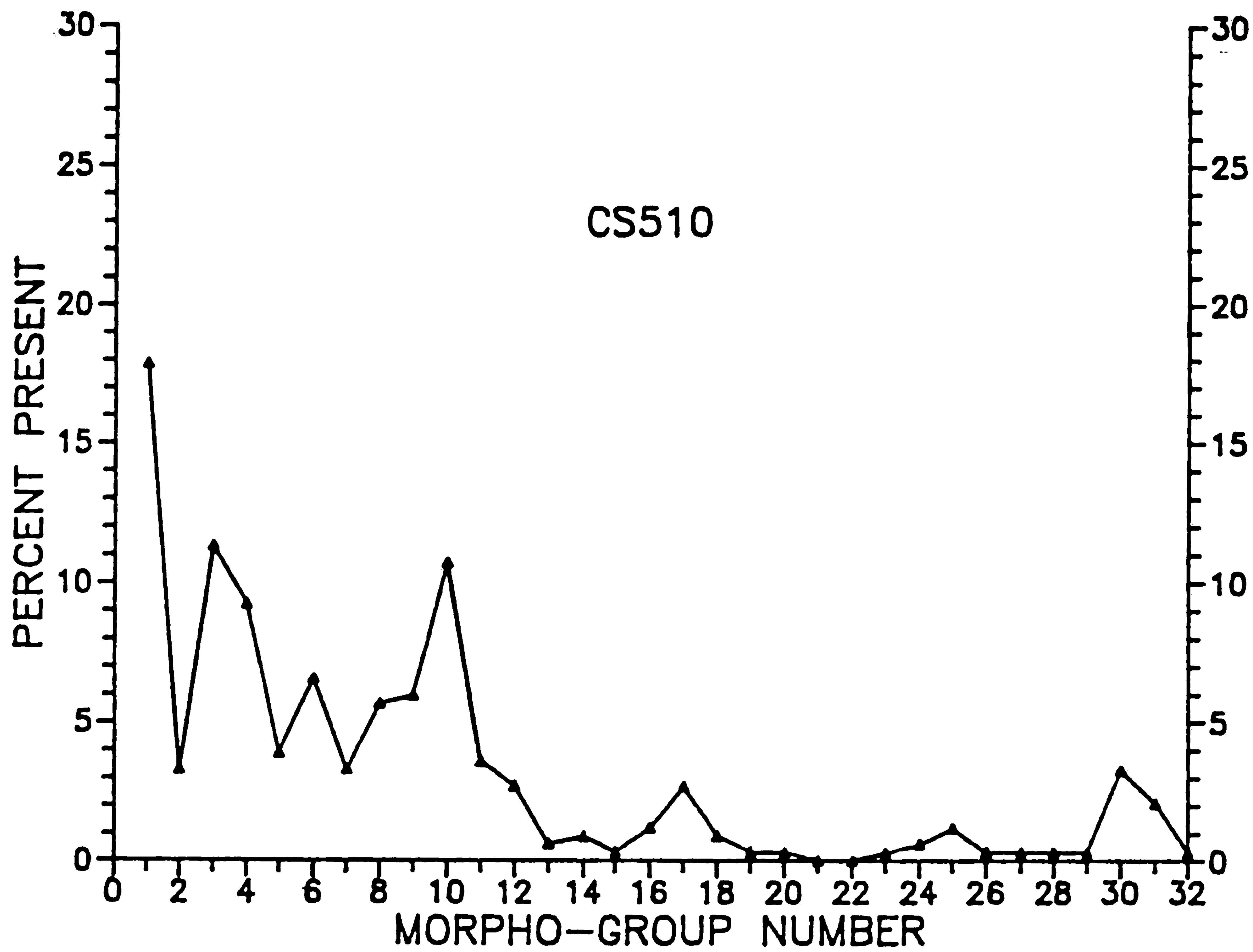
A-4: Graph of the percentages of 32 morpho-groups present within sample CW308 form "Zone" 8.



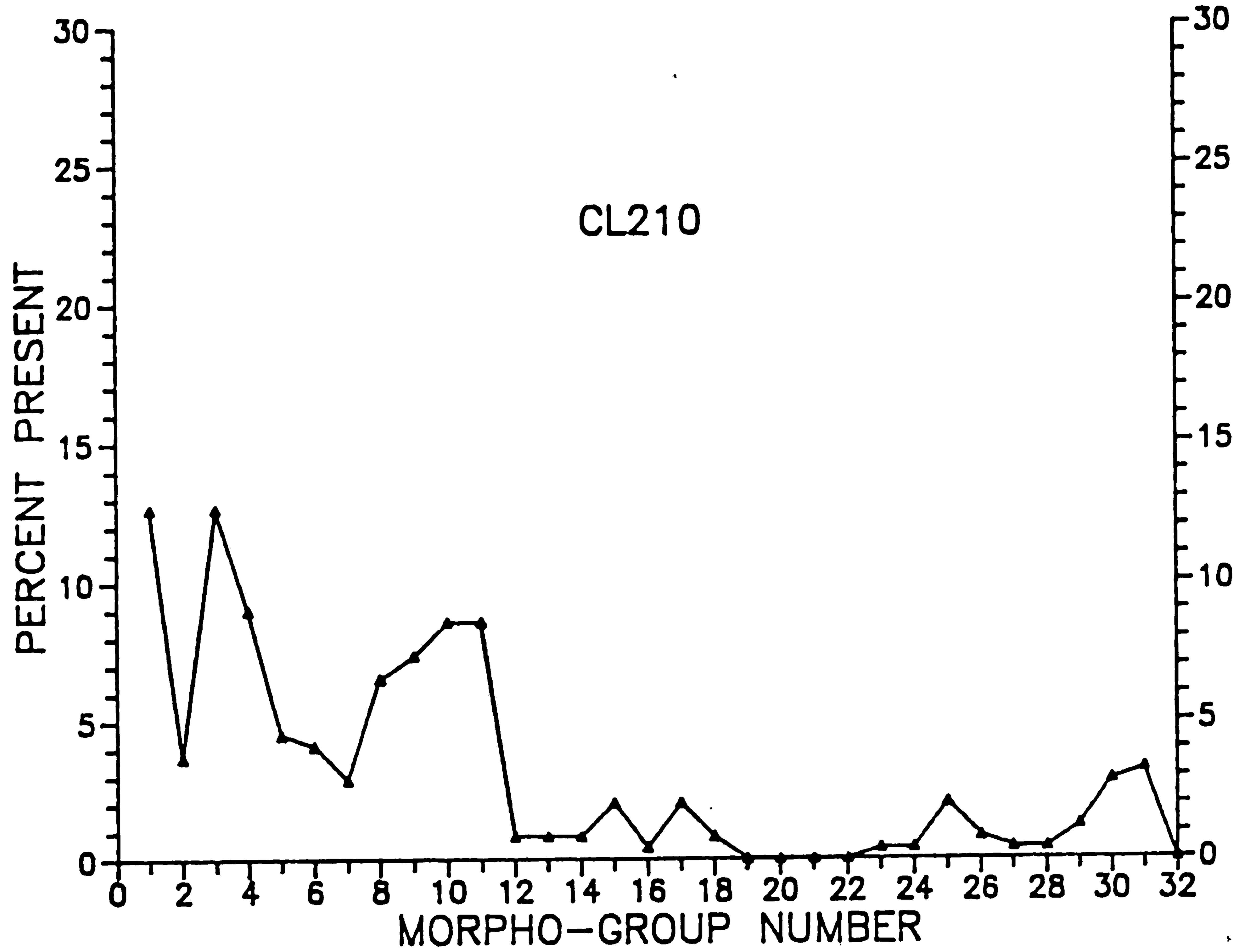
A-5: Graph of the percentages of 32 morpho-groups present within sample CS709 from "Zone" 9.



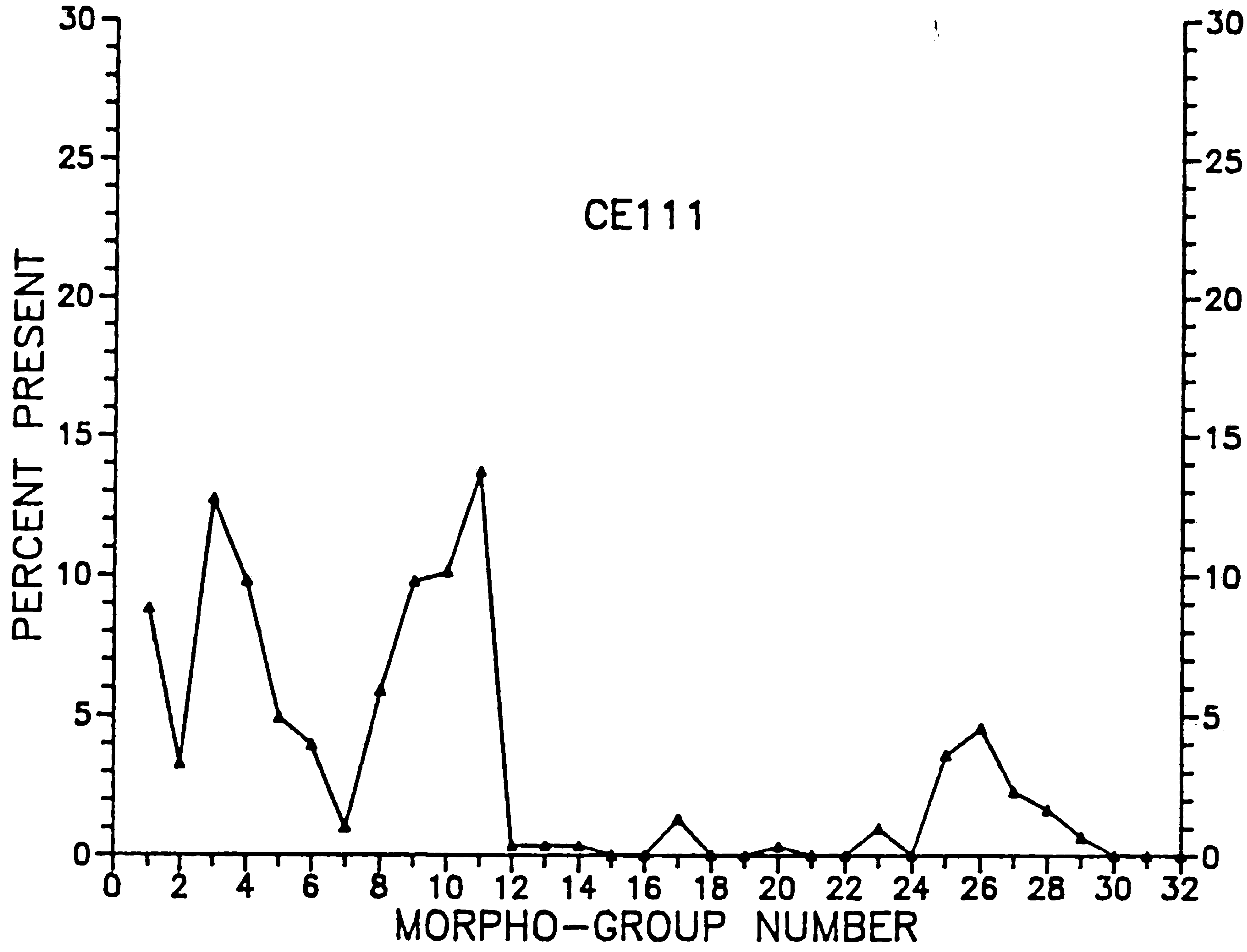
A-6: Graph of the percentages of 32 morpho-groups present within sample CW209 from "Zone" 9.



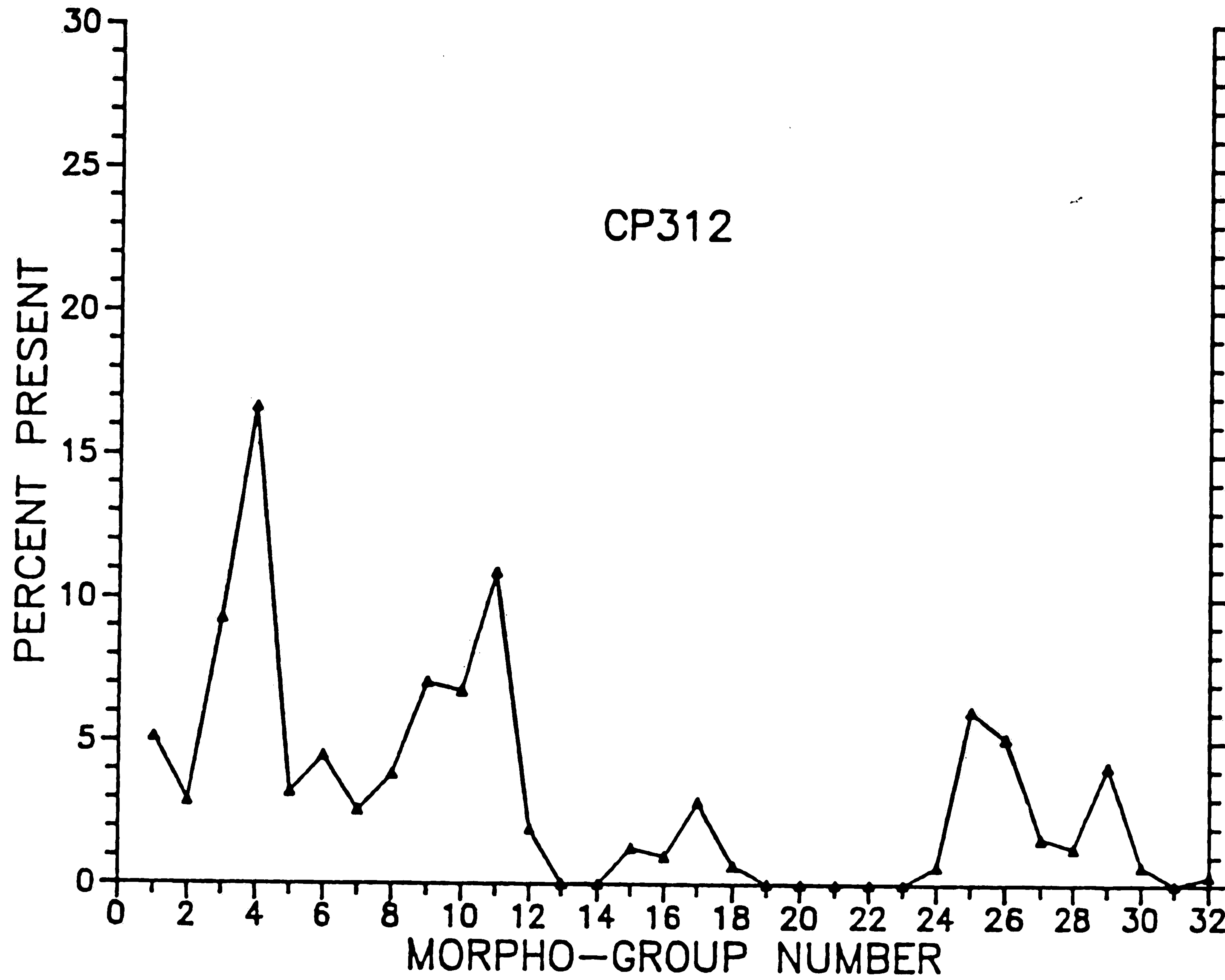
A-7: Graph of the percentages of 32 morpho-groups present within sample CS510 from "Zone" 10.



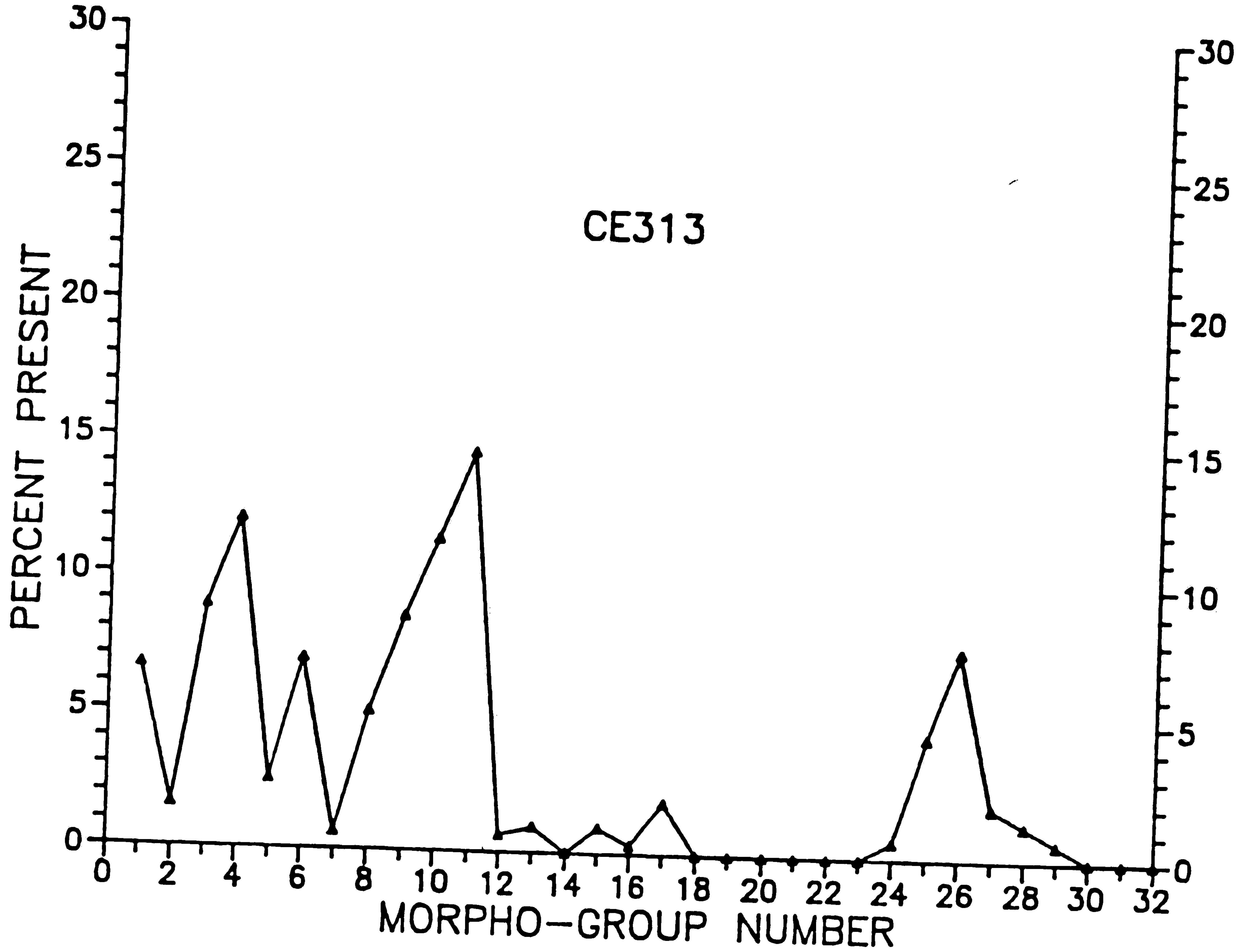
A-8: Graph of the percentages of 32 morpho-groups present within sample CL210 from "Zone" 10.



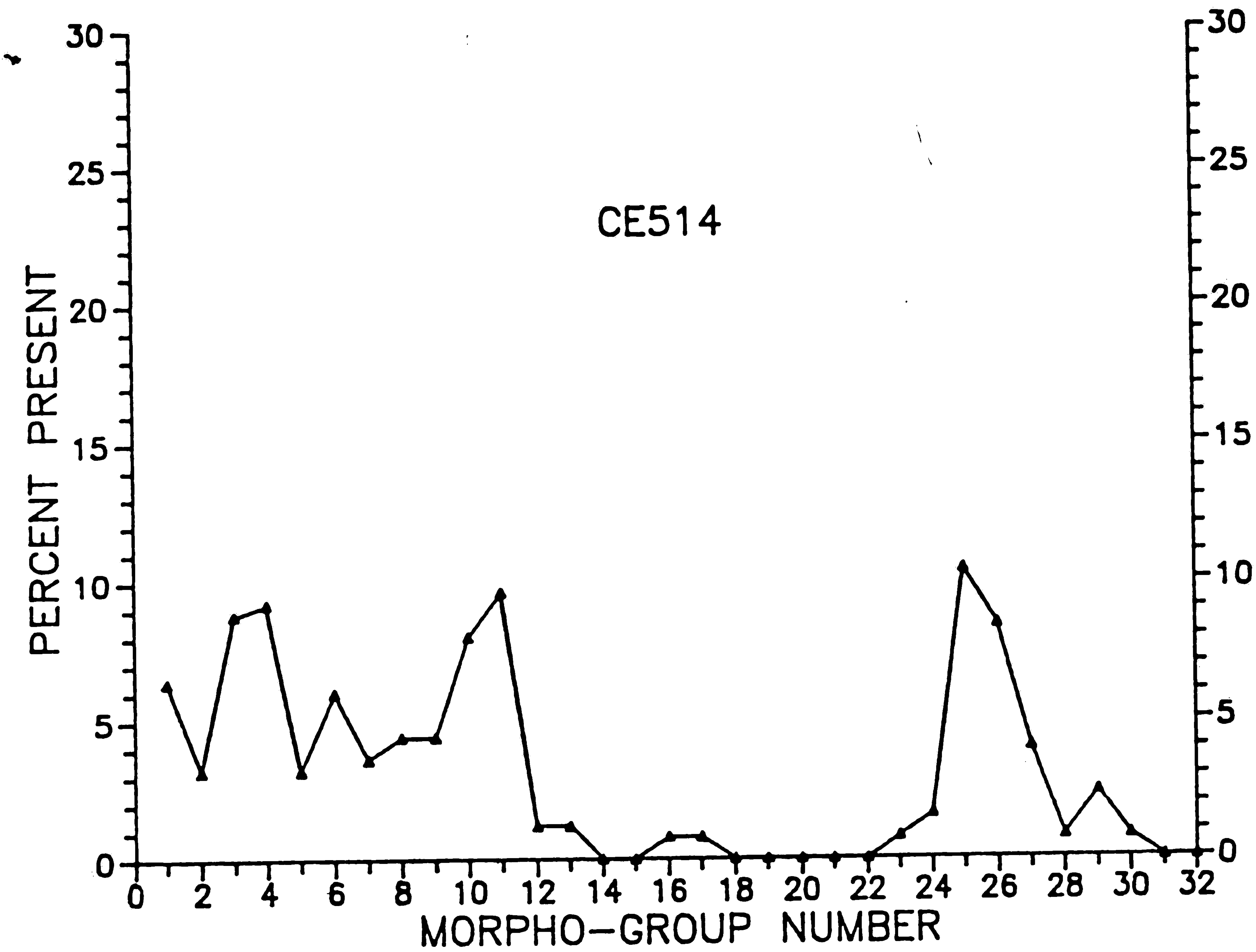
A-9: Graph of the percentages of 32 morpho-groups present within sample CE111 from "Zone" 11.



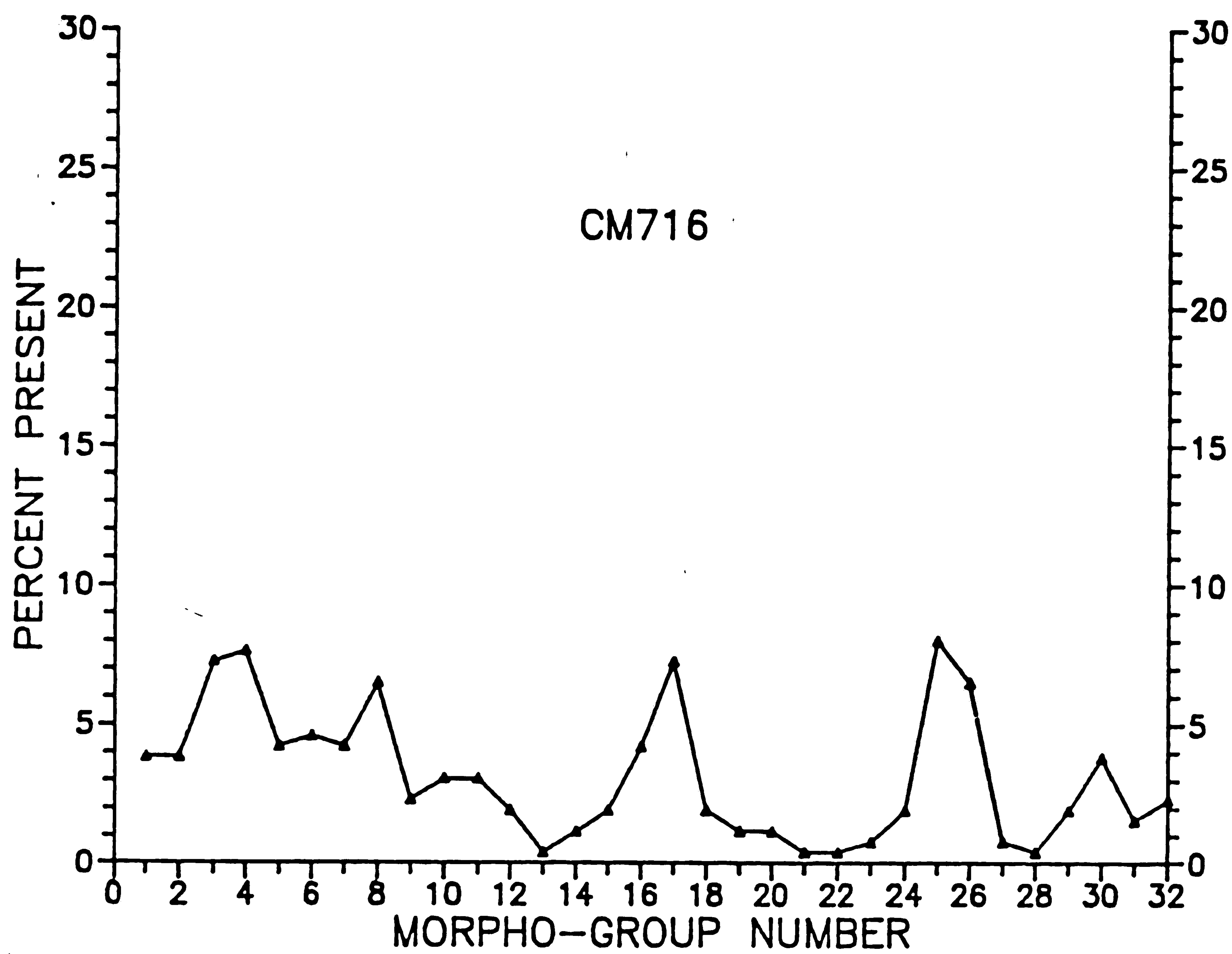
A-10: Graph of the percentages of 32 morpho-groups present within sample CP312 from "Zone" 12.



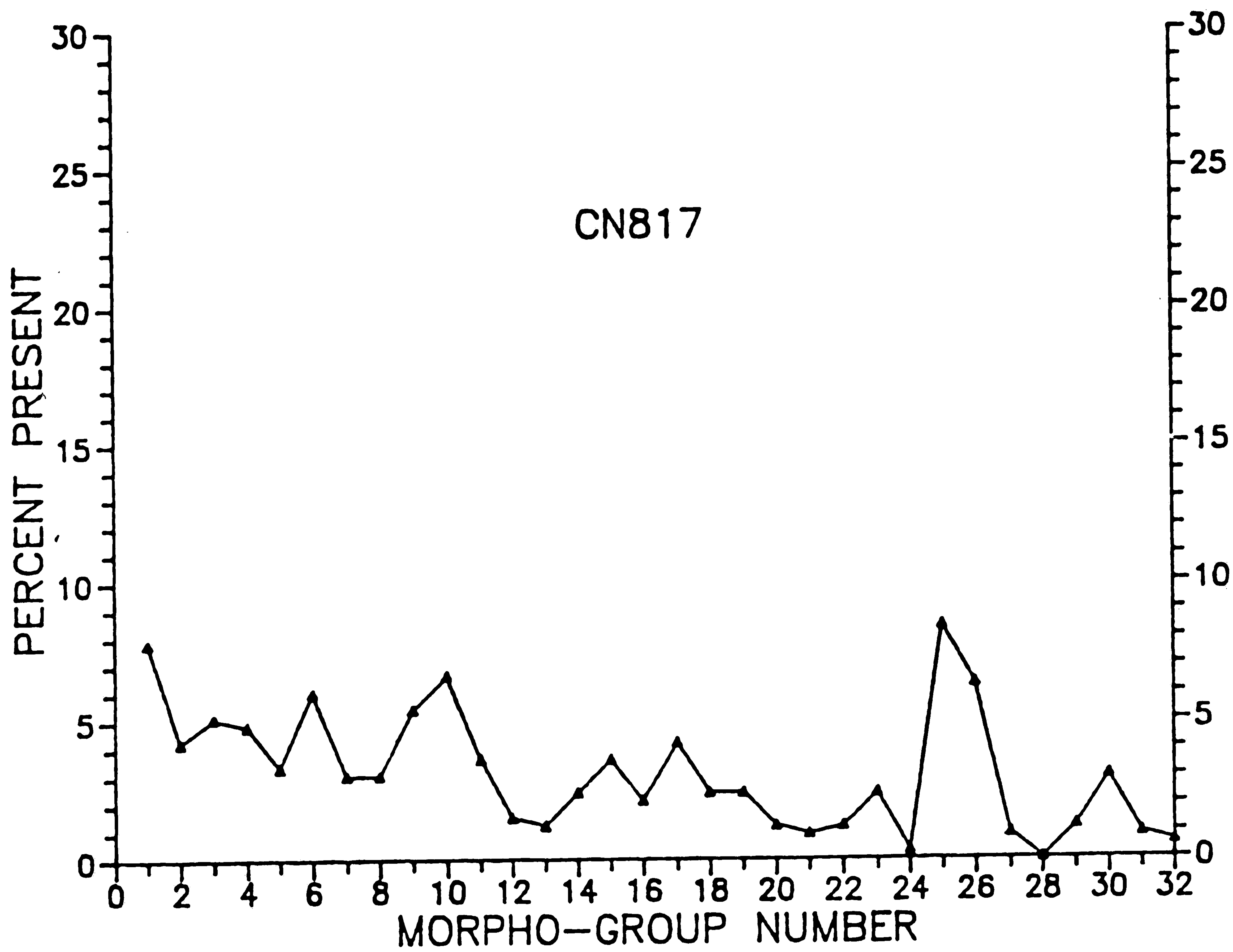
A-11: Graph of the percentages of 32 morpho-groups present within sample CE313 from "Zone" 13.



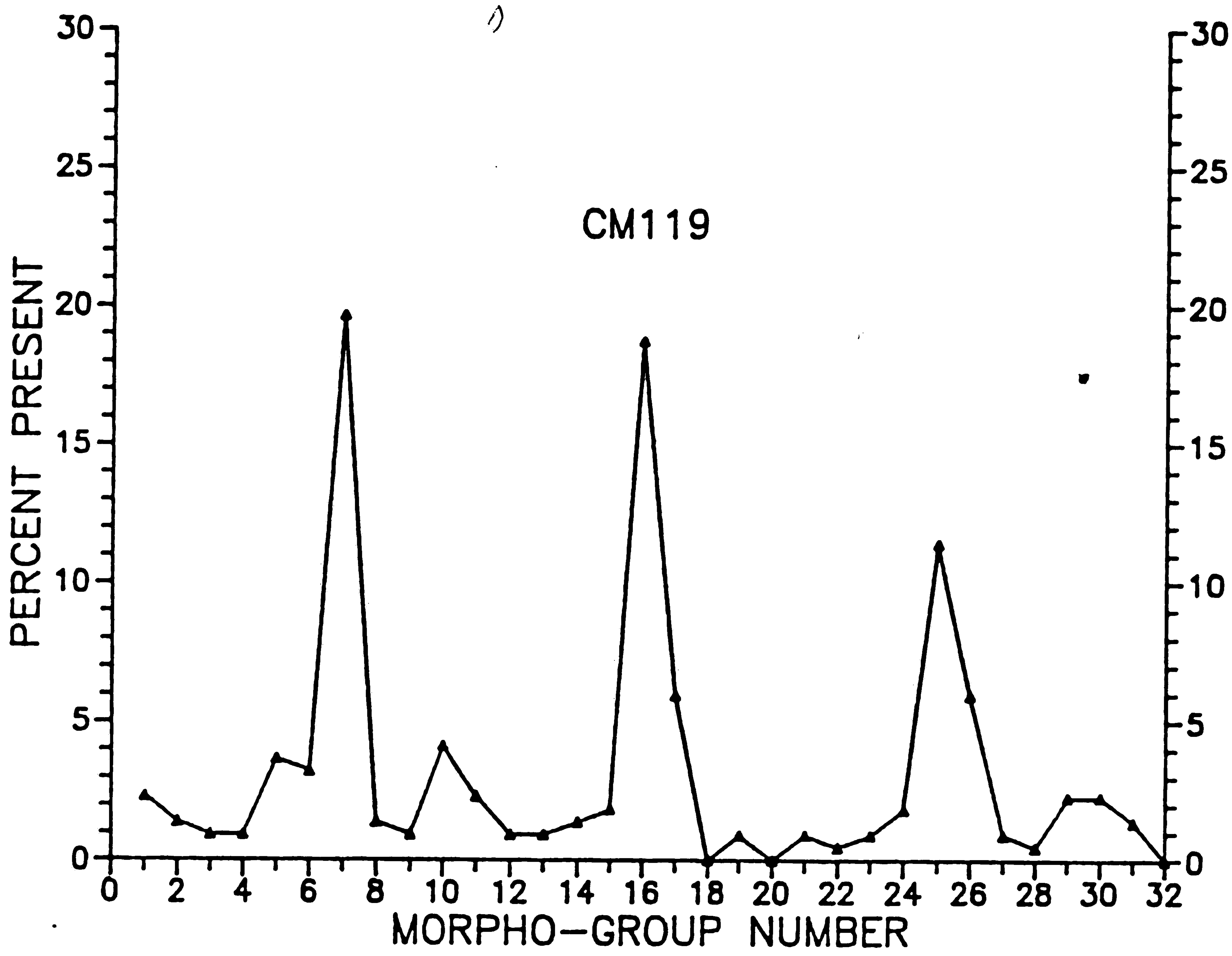
A-12: Graph of the percentages of 32 morpho-groups present within sample CE514 from "Zone" 14.



A-13: Graph of the percentages of 32 morpho-groups present within sample CM716 from "Zone" 16.



A-14: Graph of the percentages of 32 morpho-groups present within sample CN817 from "Zone" 17.



A-15: Graph of the percentages of 32 morpho-groups present within sample CM119 from "Zone" 19.

Appendix B

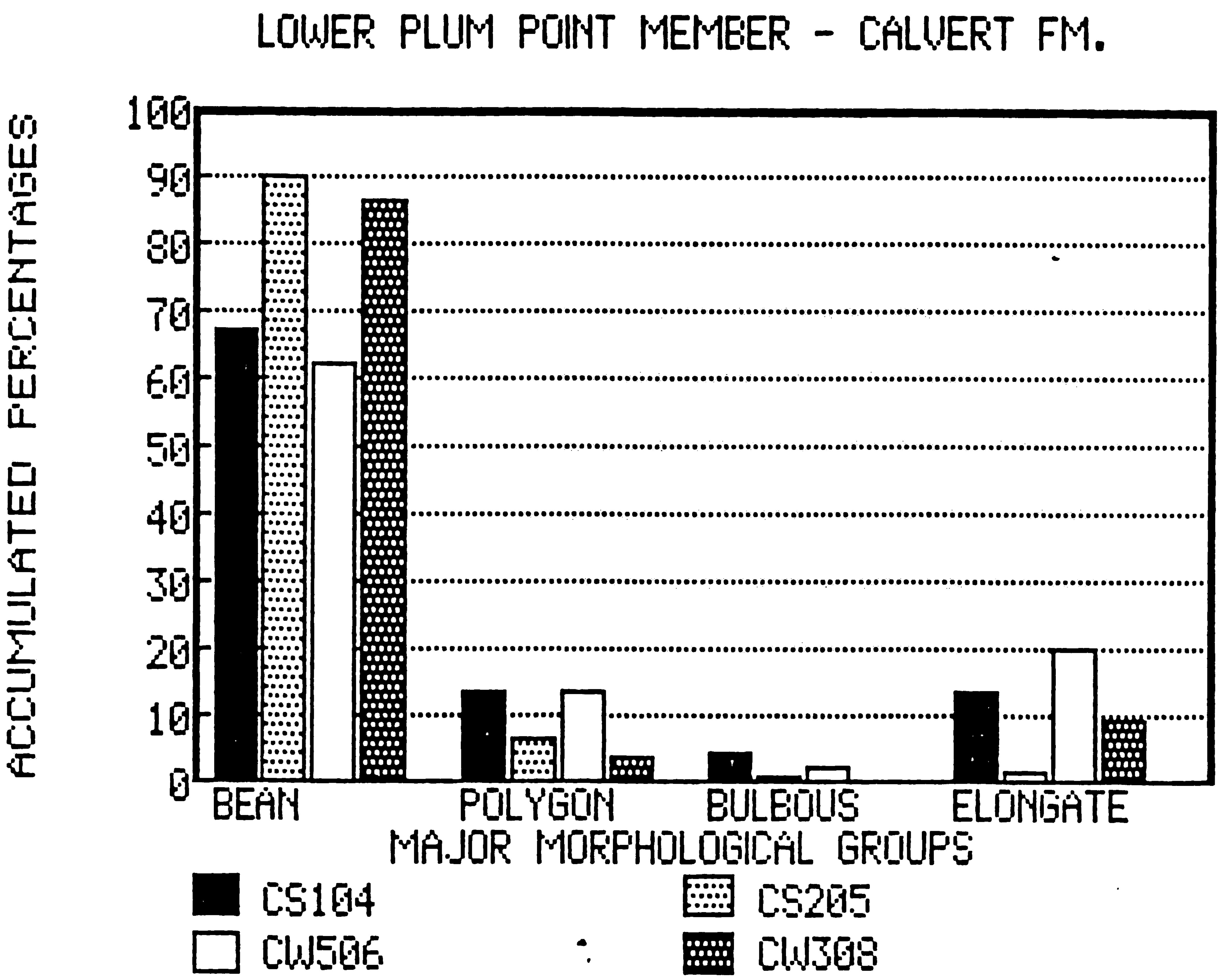
Major Morphological Groups (Percentages)

SAMPLE I. D.[1]	BEAN	POLYGONAL	BULBOUS	ELONGATE	ASYMMETRIC[2]
CM119	42.46%	27.85%	5.02%	24.66%	32.87%
CN817	55.53%	14.70%	8.40%	21.32%	23.10%
CM716	52.67%	16.41%	5.71%	25.20%	22.12%
CE514	69.20%	1.60%	2.40%	26.80%	4.00%
CE313	80.36%	3.17%	0.64%	15.83%	3.81%
CP312	74.44%	5.76%	0.64%	19.71%	6.40%
CE111	84.38%	1.63%	1.31%	12.70%	2.94%
CL210	82.04%	6.13%	0.82%	11.02%	6.95%
CS510	84.53%	5.95%	1.50%	8.04%	7.45%
CW209	81.40%	5.19%	1.73%	11.69%	6.92%
CS709	86.81%	4.06%	0.34%	8.78%	4.40%
CW308	86.57%	3.84%	0.00%	9.59%	3.84%
CW506	62.78%	14.24%	2.26%	20.69%	16.50%
CS205	90.40%	6.51%	1.02%	2.04%	7.53%
CS104	67.48%	13.70%	4.78%	14.04%	18.48%

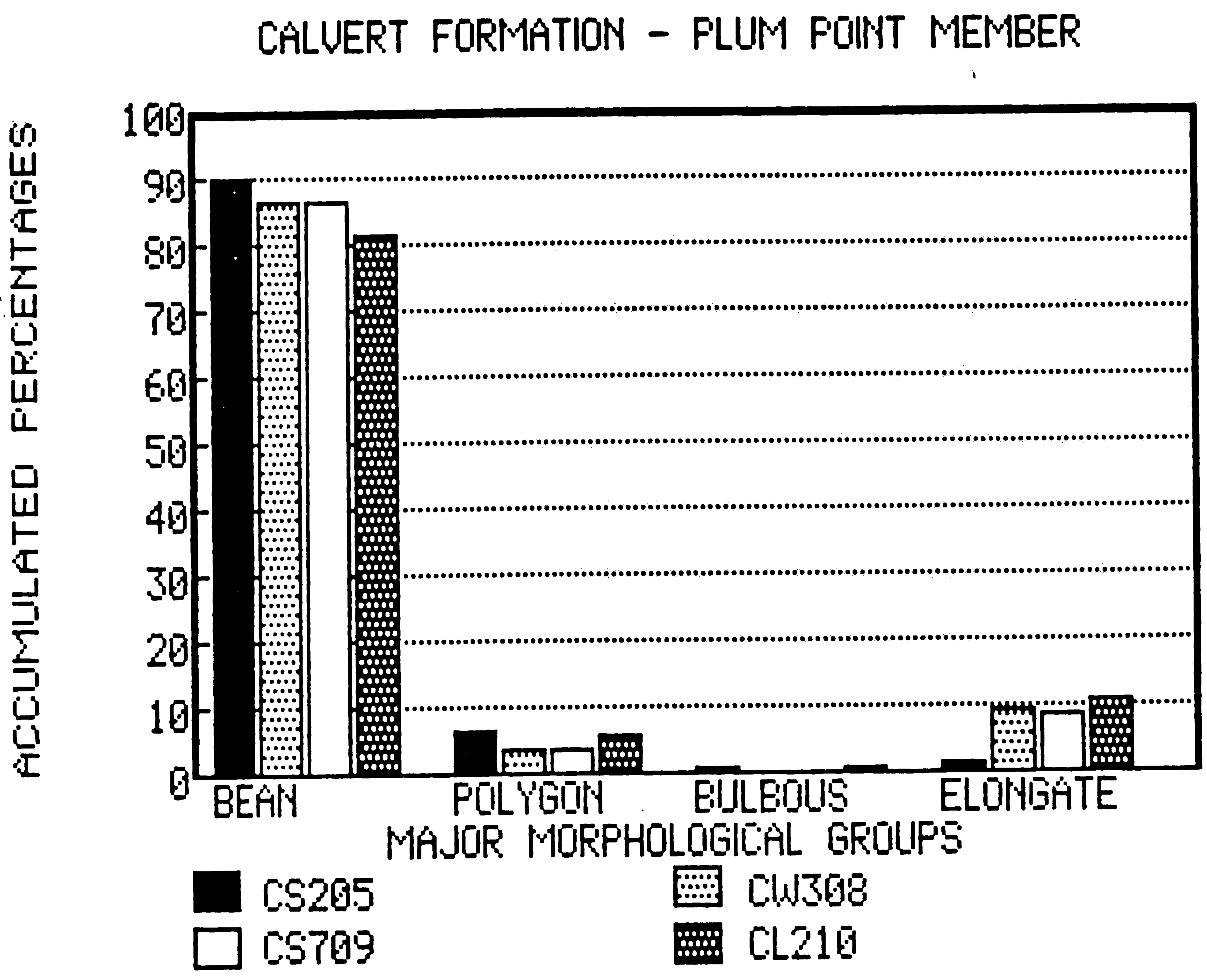
1 - Last two numbers of the Sample I. D. indicate the "Zone". For example, sample CE514 is from "Zone" 14.

2 - Asymmetric morpho-groups consist of the combined percentages of the polygonal and bulbous morpho-groups.

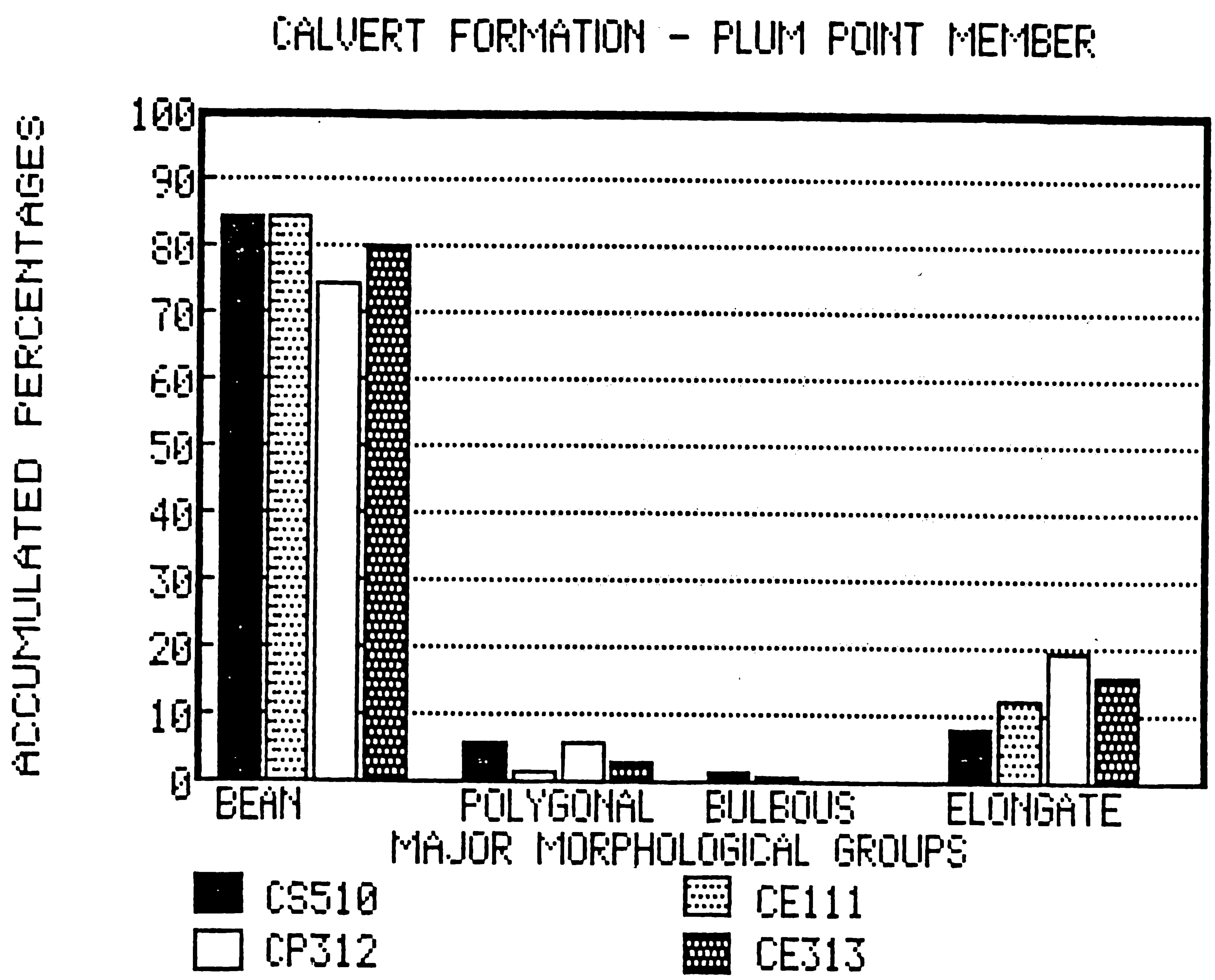
Appendix C



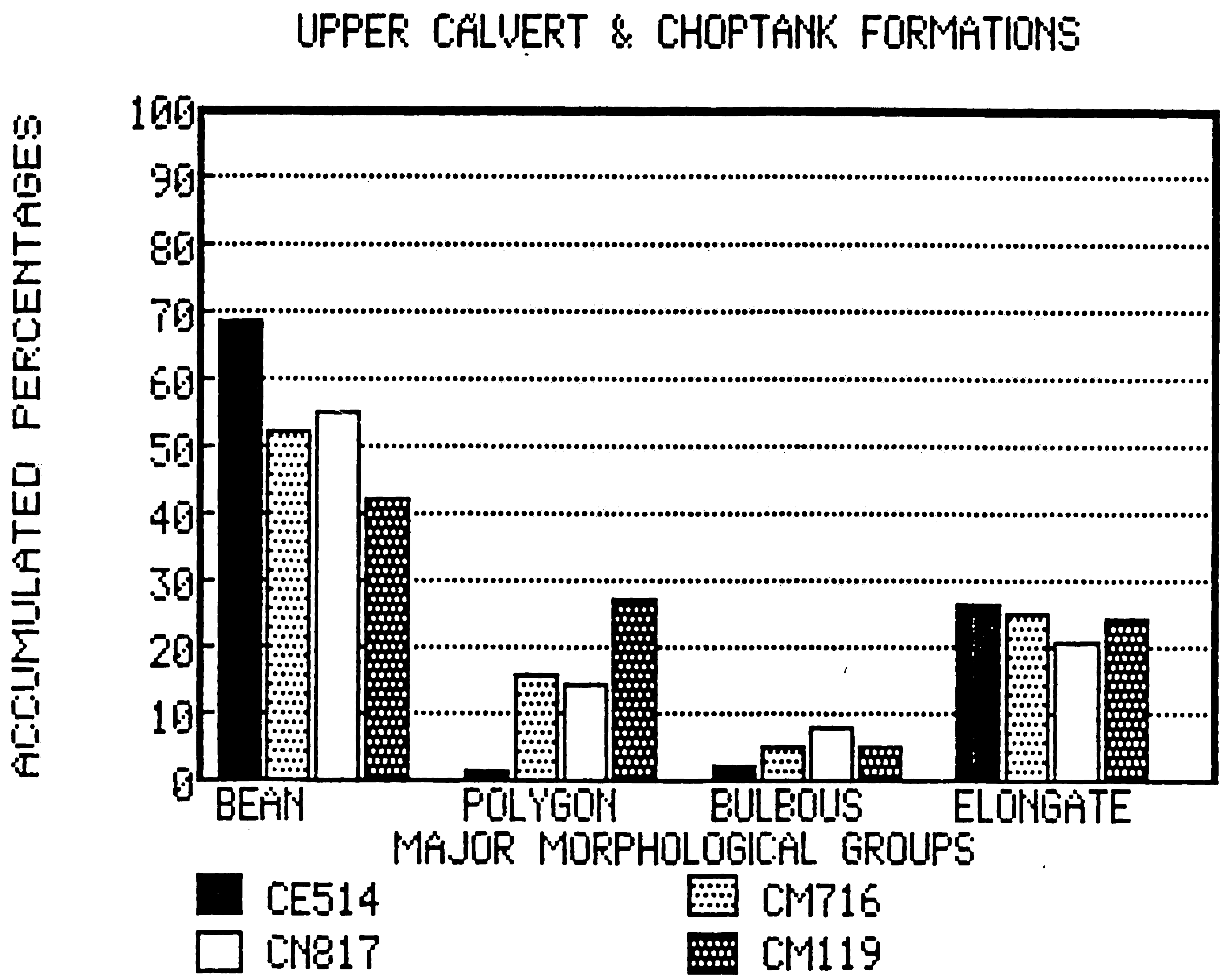
C-1: Graph of the total percentages of four major morpho-groups present within samples from the lower Plum Point Member. The last two numbers of the sample I.D. indicate the "Zone".



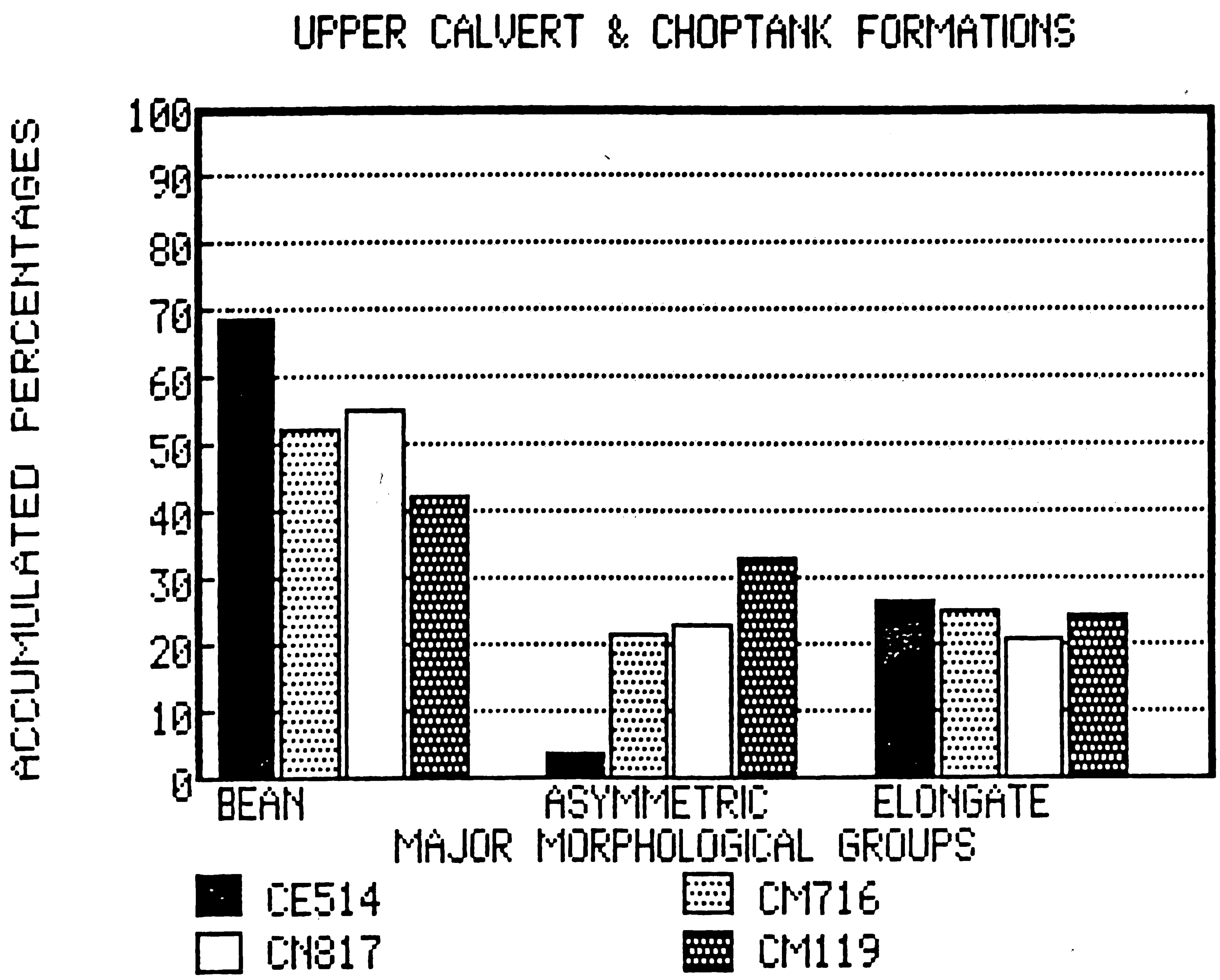
C-2: Graph of the total percentages of four major morpho-groups present within samples from the lower to middle Plum Point Member. The last two numbers of the sample I.D. indicate the "Zone".



C-3: Graph of the total percentages of four major morpho-groups present within samples from the middle to upper Plum Point Member. The last two numbers of the sample I.D. indicate the "Zone".



C-4: Graph of the total percentages of four major morpho-groups present within samples from the Calvert Beach Member (Calvert Fm.) and the Choptank Formation. "Zone" is indicated by the last two numbers of the sample I.D.



C-5: Graph of the total percentages of three major morpho-groups (asymmetric=polygonal+bulbous) present within samples from the Calvert Beach Member (Calvert Fm.) and the Choptank Fm. "Zone" is indicated by the last two numbers of the sample I.D.

VITA

Stephen J. Cauller was born to Mr. & Mrs. William L. Cauller in Allentown, Pa. on June 8, 1960. He resided in beautiful suburban Hecktown, Pa. and graduated from Nazareth Area Sr. High School in 1978. He entered West Chester University in West Chester, Pa. in September, 1978 and received a Bachelor of Science Degree in Earth Science in August, 1982.

In 1983, Mr. Cauller entered the graduate program in Geological Sciences at Lehigh University where he served as both a graduate research and teaching assistant. In October, 1985 he married Jean M. Swartchick and relocated in Phoenixville, Pa. Mr. Cauller followed the bright lights to Long Island, New York in June, 1987 to pursue a career as a hydrologist with the U. S. Geological Survey Water Resources Division and received a Master of Science Degree in Geological Sciences from Lehigh University in October, 1987.